

## AN ABSTRACT OF THE THESIS OF

Christian E. Torgersen for the degree of Master of Fisheries Science presented on July 8, 1996. Title: Multiscale Assessment of Thermal Patterns and the Distribution of Chinook Salmon in the John Day River Basin, Oregon.

Abstract approved: \_\_

Hiram W. Li

This study examined the distribution and behavior of adult spring chinook salmon (*Oncorhynchus tshawytscha*) related to patterns of stream temperature and physical habitat at channel unit, reach, and basin-wide spatial scales in both a wilderness stream and a disturbed stream in the John Day River basin in northeastern Oregon. Thermal remote sensing of holding and spawning reaches in the upper subbasins of the North Fork and Middle Fork John Day River provided spatially continuous maps of stream temperature. Multiscale associations between salmon and cool-water areas were assessed by overlaying thermal imagery with fish locations mapped during distributional surveys.

Chinook salmon were distributed non-uniformly throughout each study area, indicating that salmon selected certain reaches within each subbasin. The coldest reaches available to salmon within the Middle Fork study areas were low gradient, unconstrained reaches where the cooling influence of groundwater flow was the most apparent. In the Middle Fork, the stream currently managed for grazing and timber harvest, water temperature differences were typically 1-2°C within riffle-pool sequences and 3-4°C among reaches. The reach level association between salmon distribution and stream temperature patterns at channel unit and reach level spatial scales was strongest in the warmest study reach, the Middle Fork, and weakest in the coldest study reach, the North Fork. Pools were the preferred habitat for adult spring chinook in both subbasins; however, riffles were used more in the North Fork, the coldest subbasin. This study identified the problems and also the benefits associated with stream temperature patchiness, or discontinuity, both in

currently disturbed and in recovering riverine ecosystems. Connectivity among system components in aquatic ecosystems is generally considered necessary for maintaining long-term ecological health. However, it is heterogeneity in the landscape/hydrogeologic template that creates refuge patches in disturbed stream ecosystems, such as those in the John Day River basin. Our observations of thermal refugia occurring at multiple spatial scales, particularly in the Middle Fork John Day River, indicate that, although discontinuity may be an ecological warning sign, refuge patches in streams should also be viewed as expressions of restoration potential because they are functioning remnants of a once continuous, intact hydrologic system.

Multiscale Assessment of Thermal Patterns and the Distribution of Chinook  
Salmon in the John Day River Basin, Oregon

by

Christian E. Torgersen

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# Multiscale Assessment Of Thermal Patterns And The Distribution Of Chinook Salmon In The John Day River Basin, Oregon

## HISTORICAL OVERVIEW

The John Day River basin is unique not only in its diverse habitats and plant and animal species, but it is also the longest river system in Oregon without any permanent impoundments. Draining the fourth largest hydrologic basin in Oregon, the John Day is one of only forty-two rivers in the entire United States that are over 200 km in length and free-flowing (Benke 1990). Of these forty-two rivers, the John Day is one of only eight rivers that possess federal protection status under the National Wild and Scenic River System. The John Day River has remained free of permanent impoundments; nevertheless, it has experienced various alterations and impacts over the last two centuries of Euro-american settlement and development. The river and its wild salmon stocks have recovered from severely abusive land use practices in the 1930s and 1940s. However, public and private land owners still face numerous challenges as they continue to manage human settlement and development in the region. The objective of this study is to provide information on stream temperature and the ecology of John Day salmon to aid in the management and preservation of aquatic species and their habitats in the John Day River basin.

The John Day River currently has one of the healthiest runs of naturally sustaining spring chinook salmon (*Oncorhynchus tshawytscha*) in the Columbia River basin (Howell et al. 1985). Salmon returning from the ocean to natal streams in the upper John Day basin ascend only three hydroelectric dams: Bonneville Dam, The Dalles Dam, and John Day Dam. The migration route through the main stem John Day River, the North Fork, and the Middle Fork is unimpeded by major diversions or impoundments from the confluence with the Columbia River upstream to the headwaters. The John Day River and its North, Middle, and South forks comprise a combined linear distance of more than 800 kilometers of free-flowing river. As a contrast to the John Day chinook, salmon stocks listed under the Endangered Species Act (ESA 1973) in the Snake River drainage ascend eight dams in the

Columbia River and Lower Snake River. For Snake River salmon, seventy percent of the migration route from the mouth of the Columbia River upstream to Lewiston/Clarkston on the Snake River has been transformed from free-flowing river to reservoir (NMFS 1996).

Compared to neighboring basins, the John Day River and its tributaries are a refuge for wild spring chinook salmon, yet the spawning reaches today represent a small fraction of the probable pre-settlement (ca. 1800) distribution (Li et al. 1995). Estimates place historical numbers of spring chinook in the John Day basin at 2-6 times the current number (OWRD 1986). Historical accounts indicate that the spatial extent of chinook salmon holding and spawning habitat used to stretch farther downstream than the current distribution. In the *SNAKE COUNTRY JOURNALS*, Peter Skene Ogden (1829), a fur trader with the Hudson's Bay Company in the 1820s, notes his trappers shooting salmon in early July near the confluence of the South Fork and the main stem John Day River. Continuing downstream several days later, Ogden "reached a Snake Camp [approximately four miles south of what is now Kimberly] of fifty men with their families all busily employed with their salmon fisheries." Kimberly is located approximately 120 km downstream of the reaches currently used by holding and spawning salmon in the main stem John Day River and Middle Fork (OWRD 1986).

High stream temperatures throughout the lower reaches of the John Day River have restricted chinook salmon to the upper headwater reaches of the North Fork, Middle Fork, and main stem John Day River. Chinook salmon no longer hold in the lower reaches of the John Day because summer water temperatures frequently exceed the upper tolerance level of 25°C (Bell 1986) for adult spring chinook salmon (Table 1.)

Land use and resource extraction, such as road building, logging, and grazing, have altered the riverine environments of the North Fork, Middle Fork, and main stem John Day River (OWRD 1986). Large-scale dredge mining is no longer conducted in the John Day basin, but historic mining during the 1930s and early 1940s had a devastating impact on salmon runs in the North Fork, Middle Fork, and main stem. Dredge mining on the main stem proceeded intermittently for more than 25 years prior to 1943, and local residents interviewed in 1944 reported not having seen or heard a salmon for many years, but all mentioned abundant salmon two to three decades previous (Nielson 1944).

Table 1. Daily water temperatures at Picture Gorge on the main stem John Day River, 1994. Picture Gorge is located 34 km upstream of Kimberly and 13 km downstream of the South Fork confluence with the main stem John Day River.

Day	Daily water temperature °C		
	Mean	Maximum	Minimum
June 28	24.5	29.8	18.9
June 29	24.7	28.9	17.5
June 30	24.2	29.3	14.2
July 1	22.7	28.4	12.4
July 2	21.2	25.9	17.0

Water temperature data were collected and compiled by Ron Gaither and the Student Watershed Enhancement Team, Monument High School, Monument, Oregon.

In spite of the severe impacts of dredge mining on the population of chinook salmon in the John Day system, the stream environment and salmonid populations have shown remarkable recovery since the 1930s and 1940s. As a case in point, Nielson (1944) commented on the condition of the North Fork John Day River in the 1940s in a report for the U.S. Fish and Wildlife Service. For historical comparison, the North Fork John Day River currently has the highest quality habitat, the greatest availability of cold water, and the greatest number of chinook salmon of the three main forks of the John Day River:

Hydraulic mining operations in the headwaters caused the stream to be very turbid at the time of our first survey [in September and October 1942]. A thick layer of silt was deposited over the bottom, covering extensive areas of otherwise suitable spawning and rearing areas. Mining activities were suspended in 1942 because of the war and, when checked in 1944, the stream was crystal clear and normal stream action had practically eliminated the silt problem.

It is apparent that the North Fork was at one time an excellent spawning and rearing stream for salmon and steelhead. ***No large run of salmon has entered this stream for at least 25 years***, but some steelhead trout continue to enter [bold italics are added to original text for emphasis].

The character of the riverine landscape has changed dramatically in the John Day basin since settlement in the late 19th century, especially in areas suitable for agriculture along the main stem John Day River where cottonwood and willow riparian corridors were cleared, marshes were drained to create stable meadows, and channels were straightened to

protect pasturage (Lichatowich and Mobrand 1995). In addition to channel straightening and bank reinforcement with rip-rap, channel morphology has changed in response to riparian vegetation removal. Near the confluence of Canyon Creek and the main stem John Day River, the channel is wide and shallow today, but a description by miners attempting to cross the river in June 1862 illustrates a different morphology indicative of root-supported undercut banks: "...it's too deep and the current too strong. Besides, you notice that the bank overlies the water, and if you were once caught in a current and carried under one of those banks you could not save yourself (Anonymous 1902)." In some areas on the upper Middle Fork John Day River, the active channel width has increased 8 meters since 1881, and multiple channels have been reduced to a single wide, shallow channel (Welcher 1993).

A multitude of land use practices, such as timber harvesting, road construction, mining, agriculture, and livestock grazing, can negatively affect the aquatic environment of salmonid fishes (Chamberlin et al. 1991, Furniss et al. 1991, Nelson et al. 1991, Platts 1991). All of these human activities have occurred within the last century in the John Day River basin (Mosgrove 1980, Oregon Water Resources Dept. 1986), and though the construction of dams on the lower Columbia River is a significant cause for decline of spring chinook in the John Day River, habitat alteration throughout the basin continues to impinge on holding and spawning areas in the upper reaches of the John Day basin (Lindsay et al. 1986, Wissmar et al. 1994, Lichatowich and Mobrand 1995).

## INTRODUCTION

Effects of human land management practices on aquatic ecosystems are far-reaching temporally and spatially and must not be underestimated when considering any aspect of biological interactions in lotic systems (Bisson et al. 1991, Minshall 1993). The hierarchical spatial structure of hydrologic drainage basins and their nested network of streams require a multiscale investigative approach when assessing ecological pattern and process with respect to land use influences (Frissell et al. 1986, Gregory et al. 1991). Natural and anthropogenic disturbances in riverine systems occur across several spatial scales and affect watershed dynamics, channel morphology, and water quality both as point perturbations, e.g., chemical and thermal pollution, and as extensive areal impacts, such as agriculture and resource extraction (Decamps 1984, Meehan 1991a, Minshall 1993). The recovery of stream biota from such disturbances is dependent on the availability and function of refugia throughout the river system that provide resilience to change (Sedell et al. 1990). Refugia may occur as entire stream reaches or as localized habitats, and their relative roles in maintaining biodiversity vary through time. The inherent spatio-temporal complexity of refugia in streams makes their assessment and management difficult, but in the aim of understanding ecosystem connectivity, and ultimately restoring altered environments and their respective endangered biota, these interactive links between spatial scales across the landscape need to be understood (Franklin 1993).

The physical, chemical, and biological components of stream systems interact collectively to form and control the habitats of stream fishes. These abiotic and biotic factors are built on a physical habitat template determined by basin-wide parameters of climate, geology, vegetation, and adjacent land use practices (Poff and Ward 1990, Meehan 1991a). Habitat requirements of fish vary throughout their life history, and each stage comprises a narrow range of habitat criteria which are sensitive to anthropogenic influences. Downstream temperature regimes, for example, are influenced by forestry and other agricultural practices when upstream riparian vegetation is removed, effectively reducing shade cover and exposing the stream channel to direct insolation (Beschta et al. 1987).

Logging and the removal of riparian vegetation along tributaries subjects the whole watershed to more insolation and can lead to overall increases in annual maximum water temperatures (Hewlett and Fortson 1982, Barton et al. 1985, Beschta and Taylor 1988). This forces cold-water organisms, such as salmonids, to move upstream where their numbers may be reduced through competition for limited space and resources (Theurer et al. 1985).

Channel morphology and streamside lands affect the heating and cooling of streams by influencing the amount of sunlight incident on the stream and its cool-water sources, such as tributaries and groundwater inputs. The physical processes of heat exchange in streams are well-documented in Brown (1983), Beschta et al. (1987), and Bohle (1994). Heat exchange in flowing water is a function of net radiation (short-wave and long-wave inputs), evaporation, conduction, convection, advection (mixing with tributaries and groundwater), and change in storage. Direct insolation is a primary factor affecting stream heating, so climatic conditions, local topography, and other factors of shading directly influence the spatial patterns of downstream warming. Warm tributaries and wide, shallow channels constitute local sources for stream warming. The primary factors that contribute to stream cooling are cold inputs from tributaries and groundwater. Riparian vegetation slows the rate of downstream warming directly, by providing shade, and indirectly, by building root-supported streambanks, which typically have reduced width-to-depth ratios. Streamside vegetation and other habitat elements, such as woody debris, create habitat complexity and increase off-channel retention of cool-water pockets important as refugia for aquatic organisms (Ebersole 1994).

### **Implications of Stream Temperature**

Many cold-water species of salmonids, and the organisms on which they feed, have narrow ranges of temperature tolerance and require cool temperatures to survive and reproduce (Reiser and Bjornn 1979). Temperature relationships between aquatic organisms and their environment, as well as the potential for alterations of such systems by humans, need to be understood to insure protection of threatened fish species and other aquatic

organisms (Armour 1991). Ambient water temperatures in spawning and holding reaches for spring chinook salmon (*Oncorhynchus tshawytscha*) in the Middle Fork and the main stem John Day River frequently exceed both the thermal optima cited for spring chinook migration (16°C) and spawning (14°C) as well as the upper zone of thermal tolerance (22°C) (Bell 1986, Armour 1991, Bjornn and Reiser 1991). Elevated water temperatures such as these during peak summer months in the lower and upper John Day River system and can stress local salmonid and invertebrate populations, especially when shade from riparian vegetation is unavailable (Li et al. 1994, Tait et al. 1994).

Adult spring chinook enter natal streams in the spring, several months before spawning, when water temperatures are still within preferred tolerance zones for migration (Lindsay 1986). The salmon must then remain, or hold, in headwater streams throughout the summer, often exposed to high ambient stream temperatures and low flow conditions, especially in agricultural and grazing lands where stream flow is diverted for irrigation and shading riparian vegetation is absent. Energy expenditure in fishes increases at elevated temperatures (Wootton 1990), so the reproductive performance of migrating and holding salmon with finite energy reserves may be compromised when stream temperatures rise above preferred tolerance zones.

Cold groundwater and tributary inputs in the form of direct flow from stream banks and upwelling from within the stream bed are essential to the maintenance of stable thermal regimes and the associated aquatic fauna (Bilby 1984, Beschta et al. 1987, Ozaki 1988). These cool-water inputs serve functions important to salmonid ecology by creating thermal refugia and providing stable rearing habitat. Cold-water seeps in stream ecosystems constitute important regulators of stream temperature and also provide fishes with cool-water refugia during periods of low flow and high ambient temperature conditions. These thermal refugia protect biotic communities from extreme thermal disturbances and are the most numerous in intact riverine systems with extensive coupling of the main channel with streamside forests, floodplain forests, and groundwater (Sedell et al. 1990, Ebersole 1994).

Several species of salmon and trout have been observed to thermoregulate behaviorally by moving to cooler areas, such as seeps and confluences with cold streams, when surrounding temperatures exceed upper tolerance zones (Gibson 1966, Kaya et al.

1977, Berman and Quinn 1991). In streams of the John Day River basin, Li et al. (1994) observed higher densities of rainbow trout (*Oncorhynchus mykiss*) in watersheds with lower daily maximum water temperatures and greater riparian canopy. In the Yakima River in Washington, Berman and Quinn (1991) observed that adult spring chinook tagged with temperature-sensitive radio-transmitters behaviorally thermoregulated to maintain internal temperatures 2.5°C lower than ambient stream temperatures in surrounding habitats. Laboratory experiments with rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) have also demonstrated behavioral thermoregulation over long periods of time and with distinct diel patterns (Reynolds and Casterlin 1979, Gregory and Anderson 1983).

### **Landscape Ecological Approach**

Landscape ecology as a discipline provides the theoretical framework for assessing spatial pattern, heterogeneity, and connectivity between landscape elements at varied scales (Forman 1981, Forman and Godron 1986). The subfield of chorology, which is the study of spatial pattern and variability, is concerned particularly with the configuration and structure of land elements, patches, and corridors, in relation to the flow of information through the landscape in organismal and geologic forms (Zonneveld 1989). Individual and collective responses of stream fishes to elements of spatial pattern may be tracked from particle and microhabitat scales of centimeters up to stream network and watershed scales of kilometers (Schlosser 1991).

Organisms such as fish behaviorally respond to various chorological phenomena at different scales delineated by upper and lower perceptual constraints described as "grain" and "extent." These terms refer to the spatial resolution and areal dimension, respectively, of the landscape under analysis (Turner 1989). In the context of this study, the smallest scale of patch structure to which an organism responds, by separating one patch from another, is its "grain." This lower limit is determined by the physiological and perceptual capacity of the organism. The "extent" is the largest scale of pattern to which an organism reacts, and this is often defined by the home range of an individual (Kotliar and Wiens 1990).



Aerial thermal remote sensing provides a multiscale perspective on the patchiness of water temperature for comparison with fish distributions in lotic environments. Thermal remote sensing from a low-flying aircraft is an effective alternative to point measurement of stream temperature when continuous maps of temperature are needed (Sturdevant, pers. comm.). Obtaining information on water temperature spatial patterns is difficult, if not impossible, using continuously recording temperature data loggers at point locations. Even if complex arrays of temperature probes could be positioned throughout an entire stream reach to monitor subunit thermal patterns, the organism of interest responding to the patterns would likely be disturbed.

A forward-looking infrared (FLIR) sensor measures surface water temperature and is most effective in small streams where mixing in the vertical water column is thorough. Airborne video cameras, multispectral scanners, and thermal sensors that measure visible, near infrared, and thermal wavebands, respectively, are well-suited for vegetation and water-related applications (Avery and Berlin 1985, Ellis and Woitowich 1989, Luvall and Holbo 1991, Rango 1994). As a landscape analysis tool, remote sensing has been used extensively in resource management to evaluate fish habitat in streams, monitor aquatic vegetation, and measure stream dimensions (Overton and Mussakowski 1983, Mussakowski 1984, Crowther et al. 1995, Hardy et al. 1995). Hick and Carlton (1991) used a thermal scanner on a fixed-wing aircraft to detect cold-water areas in an Australian river that were important refugia for rainbow trout. Similar applications of thermal remote sensing can be used to detect areas with cool-water upwelling, such as tributary junctions, thermally stratified pools, and subsurface outflow, that may be critical for fishes in streams subject to high temperatures.

## **Research Objectives**

In this study, we used thermal imagery to examine spatial patterns of adult chinook salmon behavior with respect to spatial patterns of stream temperature from channel unit to basin-wide scales. We hypothesized that (i) stream temperature is patchy at varied spatial scales, and (ii) the distribution of chinook salmon is patchy and positively associated with

cool-water areas at channel unit and reach-level spatial scales. The research objectives were (1) to assess thermal patterns and identify the spatial scales at which patchiness occurs, (2) to identify thermal and habitat characteristics in key reaches utilized by chinook salmon, and (3) to compare the behavioral response of chinook salmon to thermal patterns in two river environments with contrasting geomorphology and land use.

## METHODS

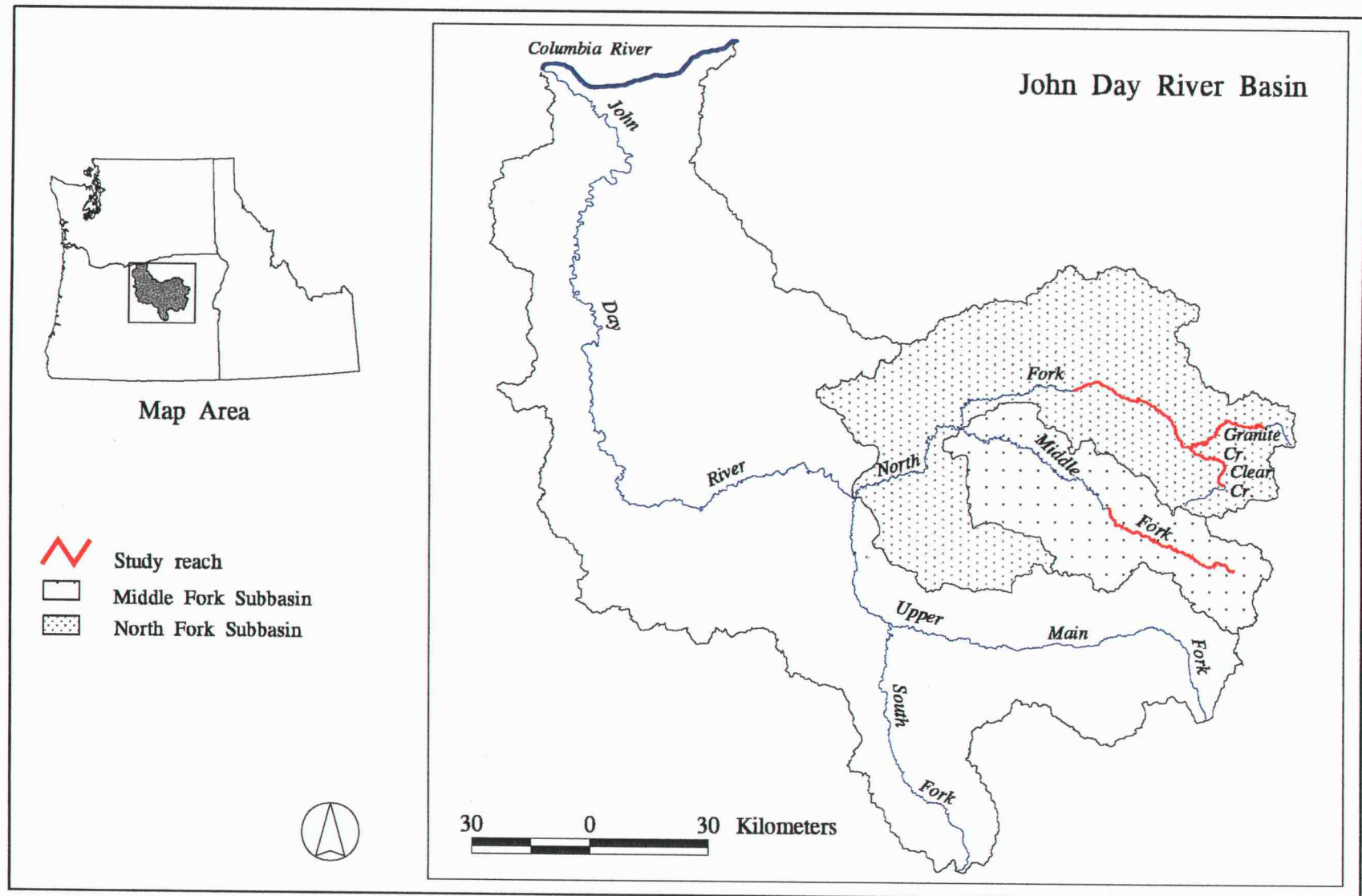
### Study Area

The study areas are the upper reaches of the North Fork (including Granite Creek and Clear Creek) and Middle Fork of the John Day River in the Blue Mountain physiographic province of northeastern Oregon (Map 1). The John Day River is a large tributary entering the Columbia River approximately 320 km from the Pacific Ocean. From the mouth of the Columbia River, an adult chinook salmon migrates upstream more than 600 km to reach the headwater reaches of the North Fork John Day River. Spring chinook holding and spawning areas are currently limited to three John Day subbasins: (1) the main stem John Day River upstream of Prairie City, (2) the Middle Fork upstream of Galena, and (3) the North Fork (including Granite and Clear Creek) upstream of Dale (Lindsay 1986, Oregon Water Resources Department 1986).

The upper North Fork and Middle Fork lie in the Elkhorn Mountains and Greenhorn Mountains, respectively, in the gold belt of the Blue Mountains (Orr et al. 1992). Columbia River basalt underlies most of the lower North Fork and Middle Fork subbasins, and the headwater reaches consist of folded metamorphosed rocks partially overlain by volcanic tuff (OWRD 1986, Orr et al. 1992). Elevations in the North Fork and Middle Fork subbasins range from 1800 m in the headwaters to 600 m near the mouth of the North Fork. The upper Middle Fork meanders northwesterly through grazed pasturage in alluvial valleys and alluviated canyons (*sensu* Frissell 1992). The North Fork flows westward through steep colluvial and alluviated canyons. Average river gradient is 0.9 percent greater in the more incised North Fork (Figure 1).

The upper Middle Fork is vegetated on the upslope primarily with *Pinus ponderosa*. Sparse riparian vegetation consists of black cottonwood (*Populus trichocarpa*) snags and willow (*Salix* spp.). In the North Fork, steep topography and well-forested upslopes characteristic of the *Abies grandis* zone (Franklin and Dyrness 1973) provide shade for the river lined with willow (*Salix* spp.) and red alder (*Alnus rubra*).

Map 1. Study area.



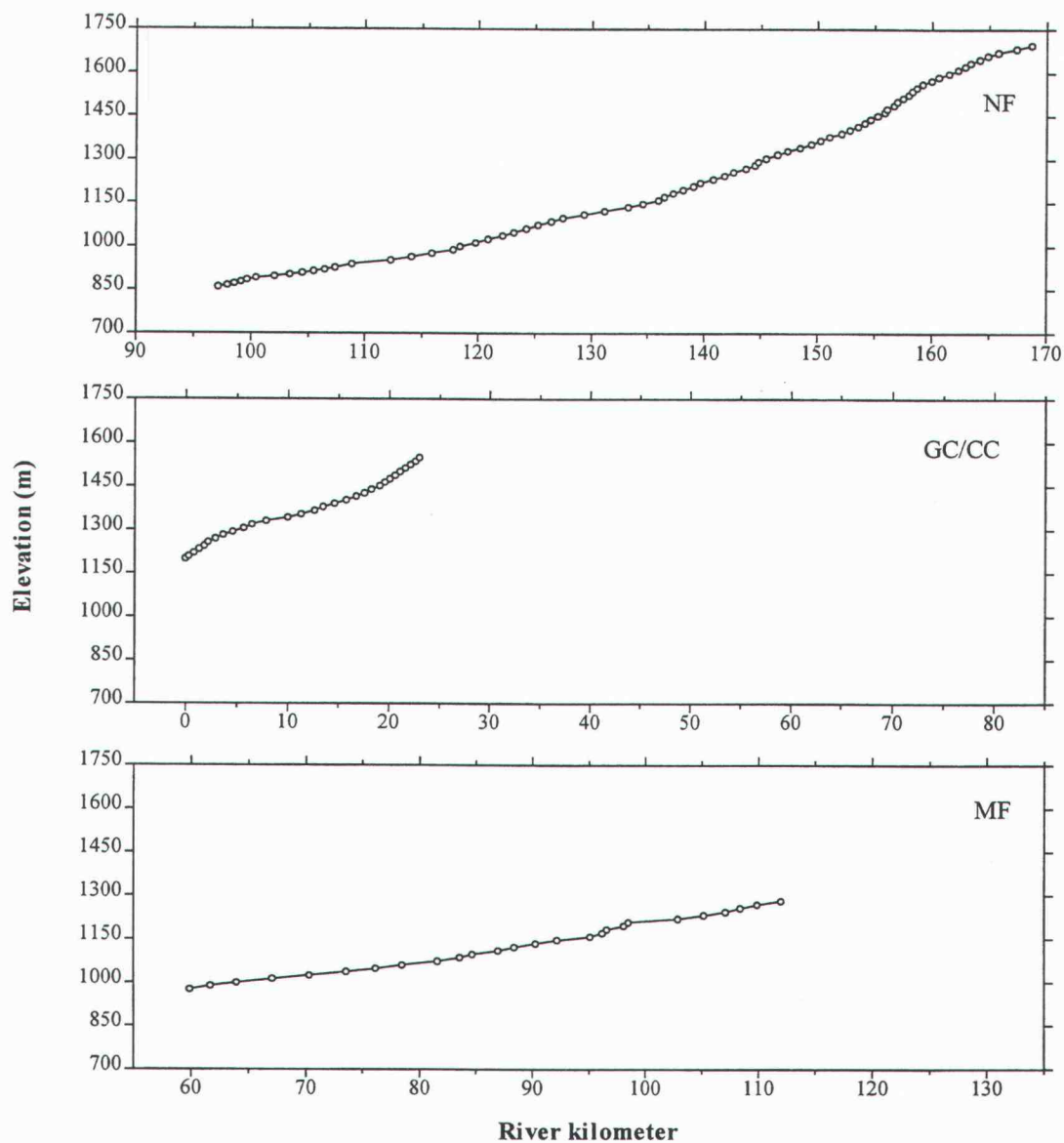


Figure 1. Longitudinal elevation profiles of the North Fork John Day River (NF), Granite Creek and Clear Creek (GC/CC), and the Middle Fork John Day River (MF). Elevations were obtained at forty foot contour intervals from U.S.G.S. 7.5 minute topographic maps.

Annual precipitation in the John Day basin is directly related to elevation, such that the lower basin receives as little as 23 cm annual precipitation, while the upper portions of the basin receive more than 100 cm. Seventy percent of annual precipitation in the John Day basin falls during the cool months of November through May, and less than 10 percent falls during the hot, dry months of summer (OWRD 1986). Daily air temperatures in the study area vary from winter lows of  $-18^{\circ}\text{C}$  to summer highs of over  $30^{\circ}\text{C}$  in the lower basin. Summer water temperatures in both the lower and upper Middle Fork approach  $30^{\circ}\text{C}$  during low flow years (Li et al. 1994, Price 1996).

The North Fork and Middle Fork form the largest tributary to the main stem John Day River and drain  $6,800\text{ km}^2$ , approximately thirty percent of the John Day basin, and they contribute over 60 percent of the average annual discharge (OWRD 1986). The respective average annual discharges of the North Fork and Middle Fork are  $38\text{ m}^3/\text{s}$  and  $8\text{ m}^3/\text{s}$  (USGS 1995). Rainfall and snowmelt contribute runoff during the peak flow months of April and May. Peak migration rates of spring chinook in the John Day basin occur during May and June (McIntosh et al. unpublished data).

Land use and resource extraction, such as road building, logging, and grazing, continue to affect the riverine environments of both the North Fork and Middle Fork (OWRD 1986). Large-scale dredge mining is no longer conducted in the John Day study area, but historic mining in the 1930s and 1940s has left a legacy of tailings in the North Fork, Granite Creek and Clear Creek, and the Middle Fork. Some small private mining claims still exist within and outside the North Fork John Day wilderness boundaries.

The Umatilla National Forest and the North Fork John Day Wilderness encompass the entire upper North Fork basin upstream of Dale. The Malheur National Forest contains most of the upper Middle Fork subbasin except for the low gradient alluvial valleys important as spawning and rearing habitat for chinook salmon. The alluvial valleys have been drained and channelized, and are currently used for cattle grazing by private landowners. Logging and grazing on National Forest lands still occur throughout both basins.

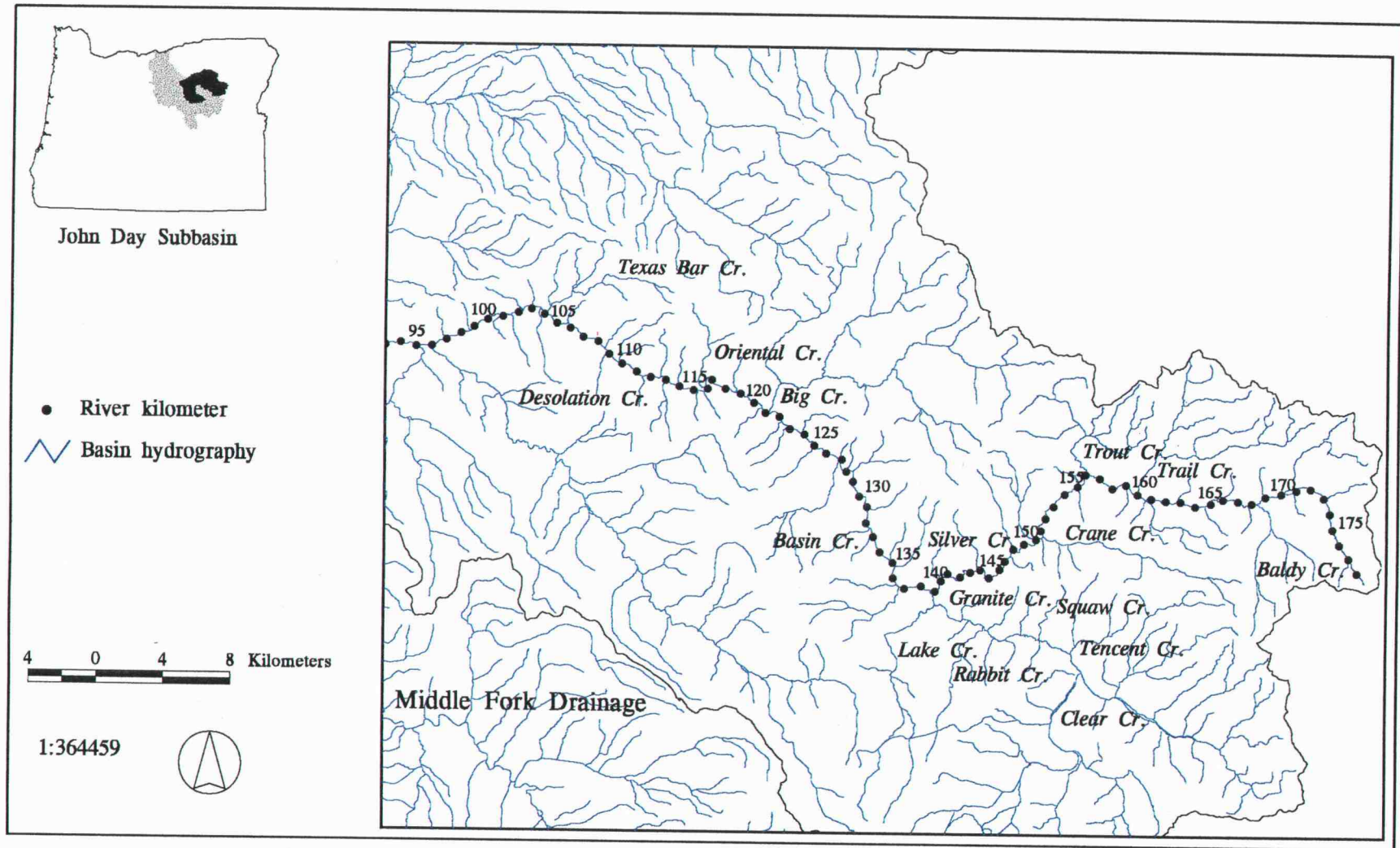


## Salmon Distribution

We used radio telemetry of tagged salmon and empirical observation of untagged salmon to assess the behavior and distribution of adult chinook salmon in the Middle Fork, North Fork, and Granite Creek/Clear Creek study reaches. Following Berman and Quinn (1991), we used radio telemetry of 12 individual salmon with internal temperature-sensitive radio-transmitter tags to track hourly, daily, and seasonal behavior of salmon with respect to ambient stream temperature fluctuations from late May through early October 1994 (Price 1996). We systematically surveyed continuous reaches of known spring chinook holding habitat, as cited in OWRD (1986), during July and August to obtain total counts of adult salmon in the North Fork (river kilometer 95-168), the Middle Fork (river kilometer 74-113), and Granite Creek/Clear Creek (river kilometer 0-20). Maps 2, 3, and 4 contain river kilometer reference locations.

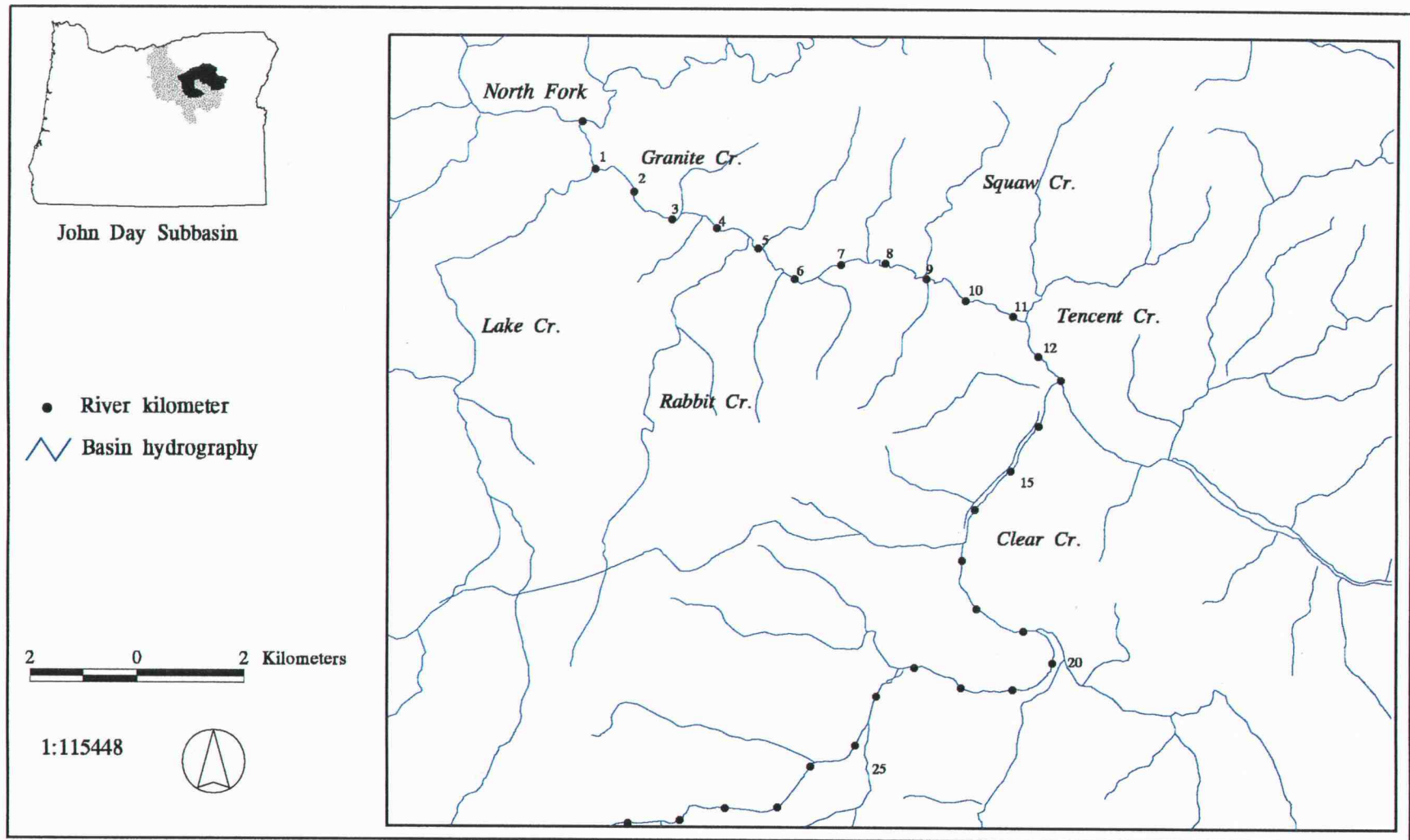
Based on the results of a radio-telemetry study during the previous year on migration patterns of John Day spring chinook, we expected the distribution of oversummering of spring chinook to vary minimally during the two month survey period (McIntosh et al. unpublished data). We counted adult salmon visually using two-person crews of a diver, equipped with mask and snorkel, and an observer/data recorder on shore. Surveys took place prior to peak daily temperatures in order to minimize disturbance to salmon. Low flow conditions and a general lack of complex cover, e.g., undercut banks and turbulence, facilitated accurate counts of adult salmon the Middle Fork study reach. In spite of excellent water clarity, visual surveys in the North Fork were complicated in high gradient reaches by swift current and turbulence. Decreased visibility due to turbulence caused divers to underestimate the actual number of salmon holding in high gradient reaches; however, observers on shore frequently counted salmon unnoticed by divers. In Granite Creek, an visual estimate, rather than a direct count, of salmon was obtained for one large pool containing many ( $> 40$ ) adult salmon. Otherwise, turbulence in high gradient reaches was the only factor complicating visual surveys.

Map 2. River kilometer key for the North Fork John Day River study reach.

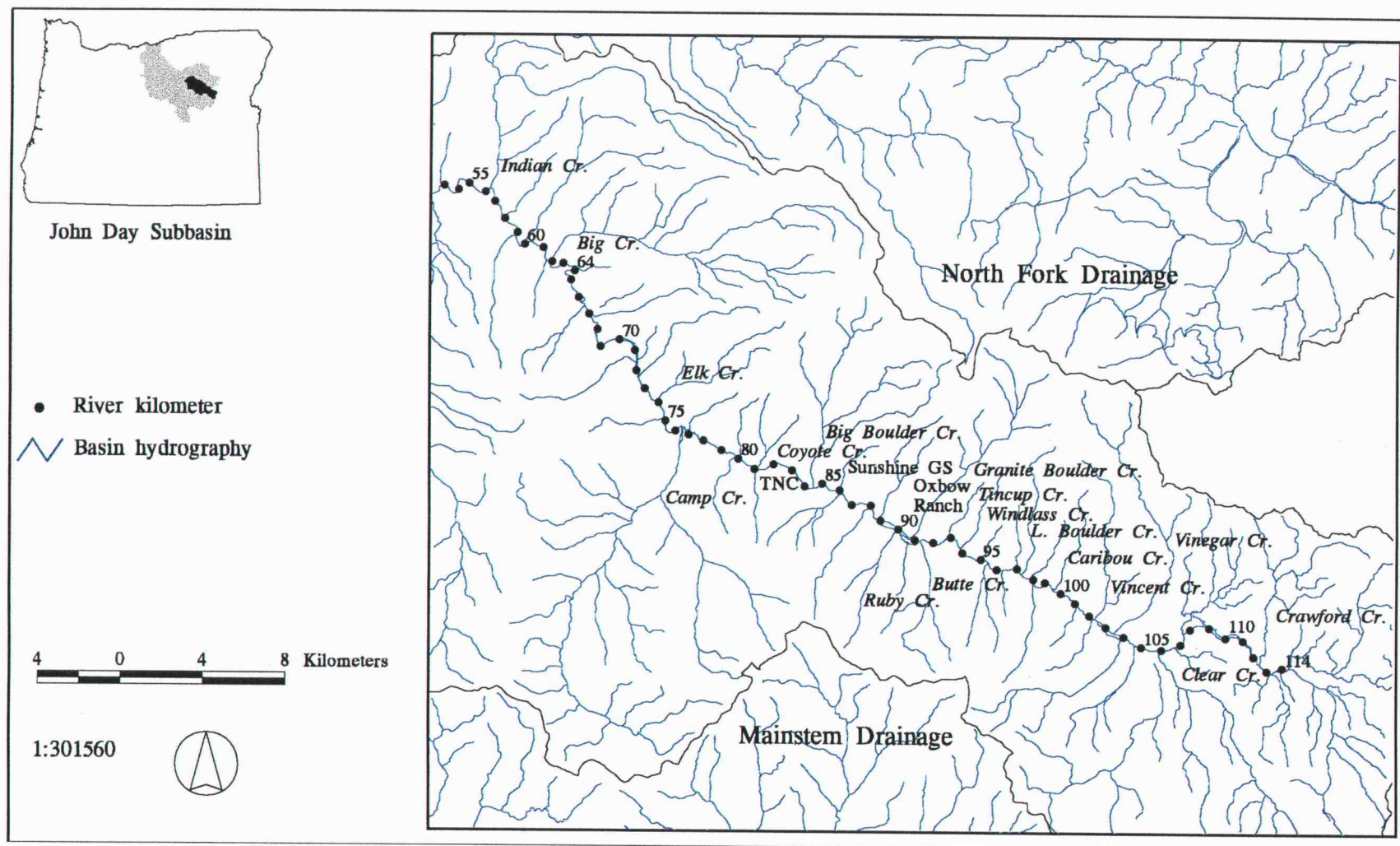




Map 3. River kilometer key for the Granite Creek/Clear Creek study reach.



Map 4. River kilometer key for the Middle Fork John Day River study reach.



We collected habitat use data on channel unit type, fish behavior, number of fish, instream cover (i.e., boulder, turbulence, large woody debris, and undercut banks), water temperature, depth, and dominant substrate composition for each channel unit containing salmon (Price 1996). Detailed hand-drawn maps of channel unit morphology, riparian cover, and fish locations at the sub-unit scale served as field references for thermal imagery. After salmon began spawning in September, we surveyed the Middle Fork and Granite Creek/Clear Creek reaches from the shore (i.e., without diving) to assess distributional changes with respect to the holding survey.

On the Middle Fork and Granite Creek/Clear Creek, we mapped the distribution of salmon and linked their locations to habitat attribute data using a Pathfinder (Trimble) global positioning system (GPS) with differential correction (accurate to 30 m), and a geographical information system (GIS). In the North Fork John Day Wilderness, where GPS battery life was not sufficient for multiple-day surveys, fish locations were noted on U.S.G.S. 1:24,000 scale topographic maps, transcribed onto 1:100,000 maps, and subsequently digitized in ARC/INFO (ESRI, Inc.) GIS. Locations of salmon in GIS layers on the North Fork are only accurate to 200 m.

We surveyed stream habitat during October in the Middle Fork (1993), North Fork (1994), and Granite Creek/Clear Creek (1994) study reaches using the Hankin and Reeves (1988) technique to estimate and verify channel unit dimensions. We used these data to assess the longitudinal distribution of pool volume and frequency of pools, riffles, and glides. Pool volumes were calculated from corrected estimates of pool surface area and mean depth.

Fish surveys on the North Fork and Granite Creek/Clear Creek are directly comparable to stream habitat estimations because both surveys took place in 1994. The habitat survey on the Middle Fork, however, was conducted in 1993, a high water year. Total annual flows for the Middle Fork at Ritter (gaging station location) in 1994 were 40 percent of 1993 flows. Actual pool volume figures from 1993 in the Middle Fork are not comparable with the North Fork and Granite Creek/Clear Creek. However, the longitudinal distribution and relative differences in pool volume within the Middle Fork study reach

were not subject to significant change between the two years because severe flooding and ice scour, which could alter channel morphology, did not occur between 1993 and 1994.

### **Thermal Patterns**

We assessed temporal and spatial water temperature patterns using data loggers at point locations and thermal remote sensing of continuous reaches. Six HoboTemp digital data loggers (Onset, Inc.) were placed individually at the upper and lower boundaries of study reaches and programmed to record temperature at 30 minute intervals in order to provide information on water temperature fluctuations throughout the summer and serve as temperature ground-truth points for thermal imagery. Data loggers (accuracy,  $\pm 0.2^{\circ}\text{C}$ ) were located in the North Fork (river kilometer 95 and 160), Middle Fork (river kilometer 61 and 109), and Granite Creek (river kilometer 5). See Maps 2, 3, and 4 for river kilometer reference. As a complement to direct measurements stream temperature, we also mapped the occurrence of cold and warm surface water inputs in the study reaches of the Middle Fork and Granite Creek/Clear Creek with a GPS during August and September. Surface water inputs included remnant side-channel seeps, stream bank seeps, seeps originating in cut-off meander and spring-fed ponds, and inputs ostensibly related to irrigation canal return flow.

We used low altitude forward-looking infrared (FLIR), obtained in the first week of August 1994, to map continuous spatial patterns of stream temperature (Figure 2). Daily stream temperatures were higher during the August 5 overflights compared to the August 8 overflight (Table 2). Thermography contractors surveyed approximately 130 km of the Middle Fork, North Fork, and Granite Creek/Clear Creek in two days at 14:30-16:00 to capture peak daily water temperatures. Thermal imagery in the 8-12  $\mu\text{m}$  wave band was collected with a Thermovision 800 (AGEMA) FLIR from a helicopter platform flying 40 km / hr in an upstream direction at 250-300 m above the river surface at an oblique angle of 35-40° from the nadir. With a 20° field of view and an image size of 140 x 140 pixels, the imagery has a ground resolution of 20-60 cm. Analog data were calibrated for an emissivity of 0.96, converted to degrees Celsius, digitized, and stored during flight at a rate

of 3 frames per second on the hard drive of an IBM PC compatible 486 computer. Time of day, frame number, and pixel statistics were stored in header files associated with each digital image.

During the overflights, we collected ground-truth measurements to compare radiant temperatures recorded in the imagery to actual kinetic water temperatures (Table 3). Water temperature measurements were made with calibrated digital thermometers, accurate to  $\pm 0.1^{\circ}\text{C}$ , in riffle and pool habitats at the surface and in the water column. Field observations of kinetic water temperature compared to radiant temperatures showed a highly significant ( $p < 0.0001$ ,  $r\text{-squared} = 0.97$ ) direct 1:1 relationship without accounting for confounding factors, such as shade, depth, and overhanging vegetation (Figure 3). The average difference between kinetic and radiant temperature was  $\pm 0.4^{\circ}\text{C}$  (0.1 SE, 0.3 SD).

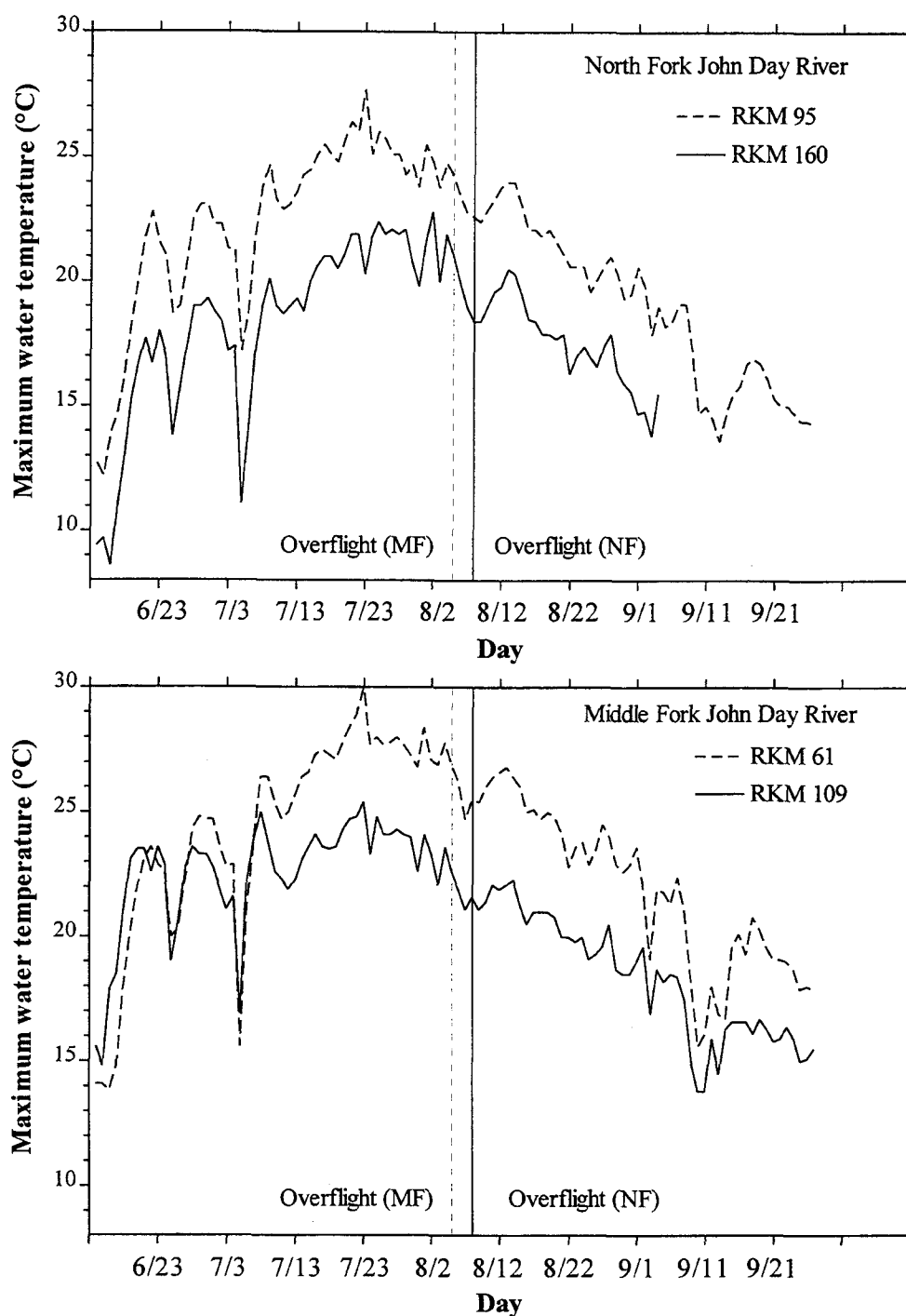


Figure 2. Daily maximum stream temperature in the North Fork and Middle Fork John Day rivers, June through September 1994. Locations of temperature data loggers are denoted in river kilometers upstream from the river mouth. The vertical dashed line indicates August 5 overflight on the Middle Fork, and the vertical solid line indicates August 8 overflight on the North Fork.

Table 2. Daily temperature means, maximums, minimums, and standard deviations for data loggers in the North Fork and Middle Fork John Day River, and Granite Creek (North Fork subbasin) on August 5 and August 8, 1994. Temperature differences facilitate comparison between August 5 (Middle Fork) and August 8 (North Fork) thermography overflights.

Water temperature conditions <sup>a</sup>	Temperature monitor location				
	North Fork John Day River		Granite Creek	Middle Fork John Day River	
	RKM 95	RKM 160	RKM 5	RKM 61	RKM 109
<i>August 5, 1994</i>					
Daily temperature °C					
Mean	21.1	15.7	19.4	21.2	18.8
Maximum	24.3	21.1	24.1	26.9	22.6
Minimum	17.7	11.4	15.3	16.6	14.7
Standard deviation	2.1	3.2	2.9	3.4	2.6
<i>August 8, 1994</i>					
Daily temperature °C					
Mean	19.5	14.1	17.4	19.5	17.8
Maximum	22.6	18.4	21.3	25.5	21.6
Minimum	16.9	10.6	13.9	15.5	14.1
Standard deviation	1.9	2.7	2.5	3.4	2.4
<i>August 5 - August 8 <sup>b</sup></i>					
Difference °C					
Mean	1.6	1.6	2.0	1.7	1.1
Maximum	1.7	2.7	2.8	1.4	1.0
Minimum	0.8	0.8	1.4	1.1	0.6
Standard deviation	0.2	0.5	0.4	0.0	0.1

<sup>a</sup> Water temperature was recorded by a data logger at 30 minute intervals.

<sup>b</sup> August 8 temperatures subtracted from August 5 temperatures.

Table 3. Ground-truth measurements of kinetic water temperature ( $K$ ) and radiant image temperature ( $R$ ) in the North Fork and Middle Fork John Day River, and Granite Creek (North Fork subbasin) on August 5 and 8, 1994.

Stream	Habitat type	Kinetic temperature °C	Radiant temperature °C	Difference $R - K$ <sup>a</sup>
Middle Fork	riffle	26.2	26.3	0.1
Middle Fork	riffle	23.6	24.8	1.2
Middle Fork	riffle	27.5	27.5	0.0
Middle Fork	pool	25.6	24.9	-0.7
Middle Fork	riffle	26.0	26.0	0.0
Middle Fork	riffle	26.0	25.5	-0.5
Middle Fork	riffle	26.6	26.3	-0.3
Middle Fork	pool	21.8	22.4	0.6
Middle Fork	riffle	22.4	22.6	0.2
North Fork	pool	21.0	21.3	0.3
North Fork	riffle	18.2	18.5	0.3
Granite Cr.	riffle	20.6	20.5	-0.2
North Fork	pool	19.8	19.5	-0.3

<sup>a</sup> The average difference is  $\pm 0.4$  °C (0.1 SE, 0.3 SD).

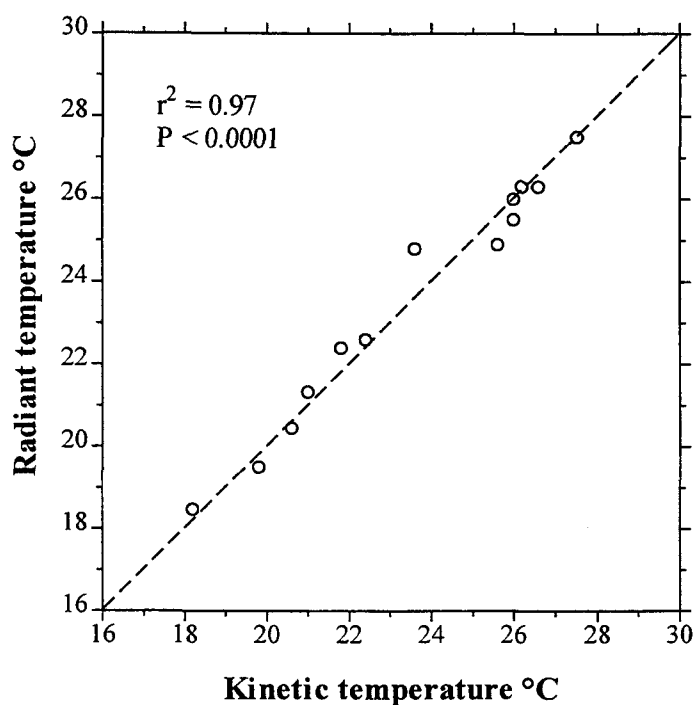


Figure 3. Linear regression of radiant (image) temperature and kinetic (ground-truth) temperature measurements. Dashed line represents a perfect 1:1 relationship.



## Image Processing and GIS

We used IMAGINE (ERDAS, Inc.) image processing software and ARC/INFO GIS on a workstation (Sun Microsystems) to analyze imagery and fish distribution data. Image processing involved four main steps: (1) extraction and decompression of raw data from 8 mm data tapes, (2) composition of image mosaics, (3) supervised classification of mosaics, and (4) superimposition of salmon locations on imagery. Raw image data (32-bit floating point) were extracted, individually or collectively, from compressed file archives according to frame reference numbers, which corresponded to the exact date and time of image acquisition. To compose image mosaics, the grayscale images were aligned individually with 20-30 percent overlap and digitally stitched in a downstream direction using a "last overlay" technique (ERDAS). Mosaicking in a downstream direction effectively masked temperature distortions on the trailing edge of each image. We used supervised classification to color-code the image mosaics in 1°C increments. With the aid of maps sketched during fish surveys, we superimposed fish locations on the thermal imagery. We made no attempts to correct for spatial distortion in the image mosaics caused by the varying oblique angle at which the imagery was collected. The images are radiometrically, but not photogrammetrically, accurate. Analyses at channel and subunit spatial scales were based on visual interpretation only; no areal measurements of temperature regions were made. We used linear measurements of known channel unit dimensions, roads, and bridges to determine the approximate map scale of each image mosaic. Map scale adjustments were necessary for each 2-4 km mosaic because the helicopter was not always able to maintain a constant height above the ground due to steep canyon walls and wind patterns.

In order to assess reach-level thermal patterns, we constructed point pattern maps of stream temperature showing longitudinal temperature patterns in each 20-70 km study reach. Using a GIS, we generated point coverages of mean, maximum, and minimum stream temperatures sampled from individual thermal images. The individual images were not referenced with GPS coordinates, so sample images were geographically pinpointed based on known landmarks. Mean spacing of temperature sample points in the three study

reaches was  $1.5 \pm 0.6$  SD river km ( $n = 101$ ). We used continuously recording data loggers in each study reach (Middle Fork, North Fork, and Granite Creek/Clear Creek) to progressively correct for elapsed flight time and associated stream temperature change. The duration of overflights in each subbasin did not exceed 1 hour, during which time stream temperature increased 0.4-1.4°C. Temperature corrections were made within, not across, subbasins.

We used two government-prepared GIS base layers in our spatial analyses: (1) hydrography -- 1:100,000 scale EPA river reach coverage, and (2) land ownership -- 1:100,000 scale BLM property boundaries. To facilitate statistical analysis of point data, such as salmon and surface water inputs distributed along linear river features, we employed the route-measure, or river kilometer, coordinate system. Using a program written by N. Poage (Forestry Science Laboratory, Corvallis, Oregon) in ARC/INFO Macro Language (AML), we generated river kilometer point coverages and assigned route-measure coordinates to salmon and surface water inputs. Stream survey data were georeferenced to  $\pm 200$  m using ARC/INFO dynamic segmentation techniques after Clarke et al. (1995).

### **Statistical Analysis**

We used contingency tables to assess the reach-level relationship between longitudinal distributions of chinook salmon and stream habitat variables. At finer spatial scales within reaches and among channel units, we examined salmon holding behavior and temperature patterns by visually interpreting fish locations superimposed on thermal imagery. For the reach level analyses, we included additional variables that are important with respect to both the habitat ecology of chinook salmon and stream temperature. These additional variables are stream gradient, channel width-depth ratio, volume of pools ( $\geq 0.7$  m in depth), and number of surface water inputs.

As explained in the preceding section on GIS methods, the records of each variable were geo-referenced with route-measure coordinates. The route-measure coordinate system enabled us to compute statistics on the linear distance between channel units containing salmon, and facilitated simultaneous analysis of all the habitat variables as a series of peaks

and troughs aligned with respect to river kilometer, the common axis. The variables were summarized longitudinally in centered 1 km bins either as sums or averages, where each bin represents a sampling unit. Number of salmon, number of surface water inputs, number of pools, and pool volume were summed in 1 km bins, whereas stream gradient, width-depth ratio, and stream temperature were summarized as 1 km means. In the longitudinal temperature profiles, we used linear interpolation, in 0.5 km intervals between actual sample points to facilitate bin averaging. The three advantages of the centered 1 km bin approach are that (1) data are summarized according to the specified spatial scale of analysis, i.e., reach-level, (2) geographic positioning of the data along the linear reach is preserved, and (3) the analysis is suited to the coarseness of the longitudinal temperature profiles.

The primary objective of statistical analysis was to compare peaks and troughs, or patchiness, in numbers of salmon with stream temperature patterns along the longitudinal stream profile. We expected the point pattern of salmon along the river to take one of two theoretical forms: (1) a uniform distribution, with the salmon evenly distributed throughout the study reach, or (2) a clustered pattern, e.g., with the salmon clumped either in one short reach or in several disjunct patches. The null hypothesis was that the longitudinal distribution of salmon is independent of habitat variables. The working hypothesis was that salmon congregate in reaches with preferred habitat, i.e., relatively cool water, and avoid reaches with unsuitable habitat.

We constructed 2 x 2 contingency tables based on expected and observed values of salmon numbers and habitat variables (Table 4). Expected values were derived by calculating densities or means of habitat variables in each study reach (Table 5). We used reach density, i.e., the number of units (e.g., salmon, pools, etc.) per linear kilometer, as an expected value for salmon numbers, pool volume, and surface water inputs because it approximates a uniform, or non-patchy distribution. The reach mean was used as an expected value for stream temperature, stream gradient, and width-depth ratio. We defined reach lengths, used in density and mean calculations, as the linear distance between the uppermost (upstream) and lowermost (downstream) salmon in each subbasin.

Fisher's exact test and chi-square statistics were applied to test for independence between contingency table categorical variables using Prism (Graphpad Software, Inc.) statistical analysis software. After Griffith and Amrhein (1991), the three assumptions of contingency table analysis with chi-square and Fisher's exact test are that (1) there must be at least two mutually exclusive and collectively exhaustive categories for each of the two classification variables; (2) the observations are independent; and, (3) the expected frequency ( $e_i$ ) must satisfy applicable restrictions, i.e.,  $e_i \geq 5$ .

Table 4. Example of a 2 x 2 contingency table of stream temperature and number of salmon. We used Fisher's exact test to assess independence between patches in stream temperature and clusters of salmon. This hypothetical table shows a significant indirect association between salmon and temperature. The greatest proportion of salmon were observed in reaches where temperature was less than expected.

Stream temperature	Salmon (no.)	
	Observed > expected	Observed < expected
Observed > expected	10	20
Observed < expected	60	10

Fisher's exact test P-value < 0.0001.

Table 5. Means and densities used as statistical expected values in contingency table analysis of salmon number and stream habitat variables in study reaches of the North Fork and Middle Fork John Day River, and Granite Creek/Clear Creek (North Fork subbasin).

Category	North Fork John Day River	Granite Creek, Clear Creek	Middle Fork John Day River
<i>Expected values</i>			
Density <sup>a</sup>			
Holding salmon (no. / km)	4.8	5.8	2.7
Spawning salmon (no. / km)	NA	7.6	3.6
Surface water inputs (no. / km) <sup>b</sup>	NA	3.1	5.4
Pool volume (m <sup>3</sup> / km)	1,044.0	2,561.7	416.4
Mean <sup>c</sup>			
Stream gradient (%)	1.2 (74)	1.4 (29)	0.6 (25)
Water temperature (°C)	20.8 (45)	20.8 (19)	23.8 (42)
Width:depth	47.8 (959)	36.5 (271)	34.3 (725)

<sup>a</sup> Density between highest and lowest salmon, seep, or pool within the reaches surveyed is used as an expected value because it approximates an even, or non-patchy, spatial distribution.

<sup>b</sup> Surface water inputs include tributary confluences, seeps, and irrigation return flow.

<sup>c</sup> Values in parentheses are sample sizes (n) for means.

## RESULTS

### Descriptive Summary

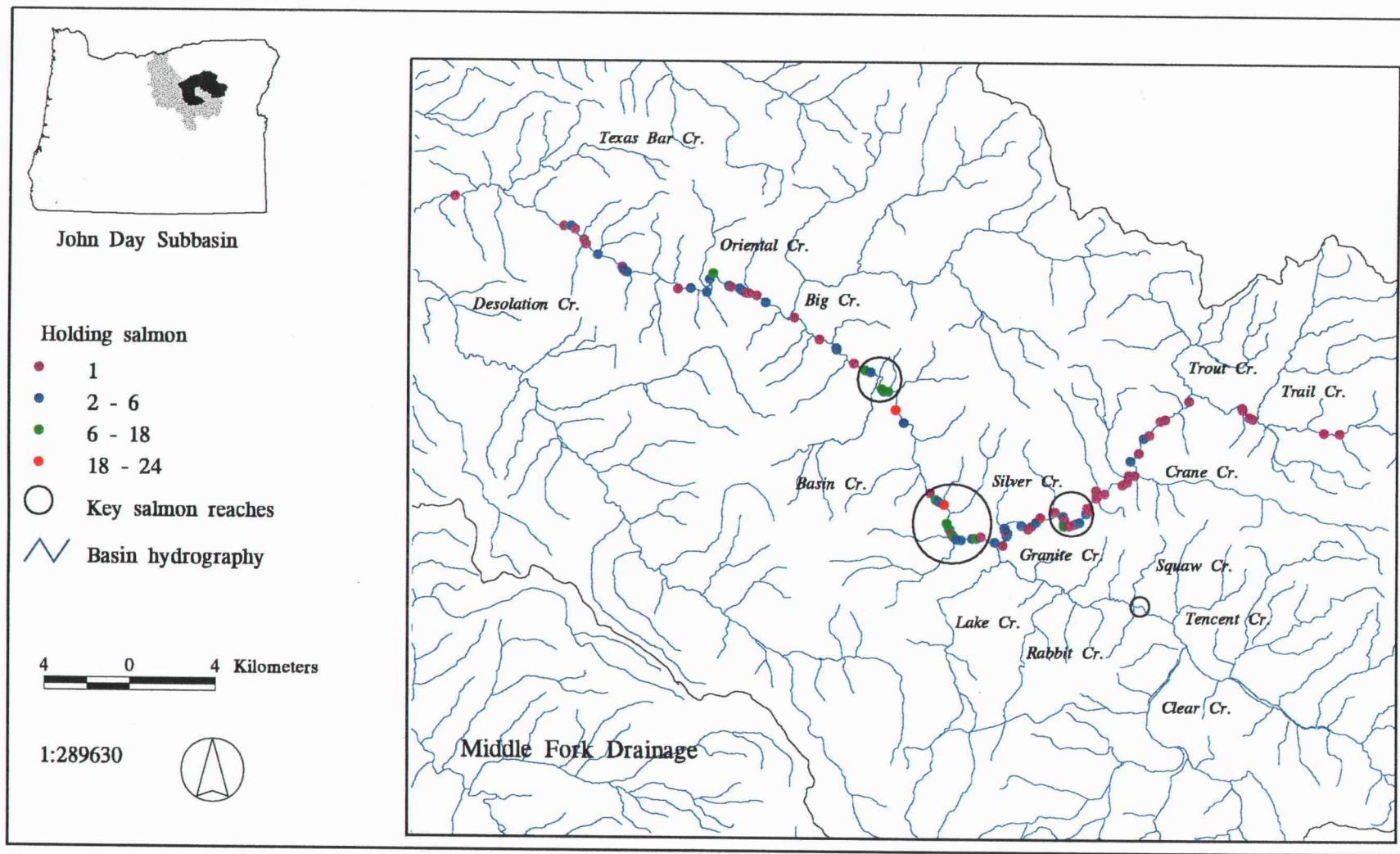
#### Salmon Distribution

Adult spring chinook were distributed unevenly within each of the study reaches, indicating preference for certain key reaches (Maps 5, 6, and 7). Density of salmon was highest in the Granite Creek/Clear Creek subbasin; however, the total number of salmon was greatest in the North Fork study reach (Table 6). Eighty-six percent of the salmon holding in the Middle Fork were found in low gradient, privately-owned reaches compared to the more constrained, publicly-owned reaches. All major holding reaches in the Middle Fork were located in low gradient, alluvial valleys. In the North Fork and Granite Creek/Clear Creek, the vast majority of holding salmon occupied public land. The number of salmon per individual channel unit differed markedly between the Middle Fork and the North Fork subbasin (including Granite Creek/Clear Creek) (Table 7). The percentage of salmon occupying channel units singly (i.e., one fish per unit) in the Middle Fork is more than twice that in the North Fork and Granite Creek/Clear Creek. Forty-five percent of the salmon in Granite Creek were concentrated in one large, deep (3 m) pool, which was deeper, but not significantly larger in volume, than any pool in the Middle Fork or North Fork study reaches. The number of salmon per channel unit was more variable in the North Fork, most likely because it is the largest stream and longest (73 km) study reach (Table 7).

Spawning salmon in the Middle Fork and Granite Creek/Clear Creek congregated in different reaches compared to the reaches identified during holding surveys (Maps 8 and 9). Granite Creek salmon selected habitats on private land more for spawning than for holding (Table 6). In both study reaches, salmon distributed themselves more evenly throughout holding reaches and concentrated near tributary confluences, i.e. Clear Creek (Granite Creek subbasin), and Clear Creek (Middle Fork subbasin). Compared to the holding distribution, higher percentages of spawning salmon were observed singly, or in groups of two or three in both subbasins (Table 8). We counted more salmon during spawning

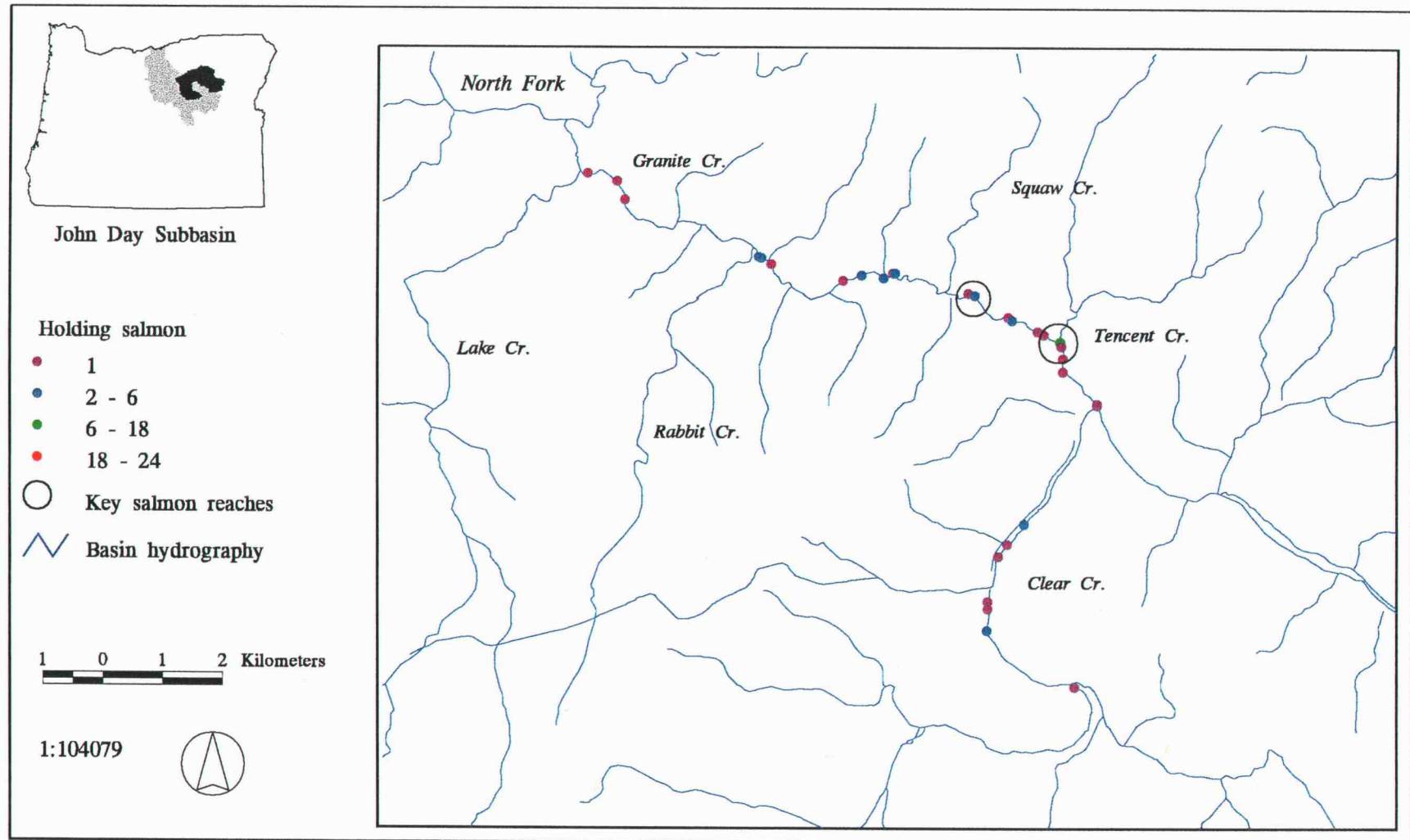
surveys than in holding surveys in both the Middle Fork and Granite Creek/Clear Creek. Radio-tracking data from the previous year indicate that salmon moved into Granite Creek and Clear Creek in the fall to spawn after holding in the North Fork over summer (McIntosh et al. unpublished data). This possibly explains the increased numbers of salmon in Granite Creek and Clear Creek during spawning surveys. Movement of salmon into the Middle Fork from the North Fork was highly unlikely due to high water temperatures and shallow water in the lower reaches of the Middle Fork. An increase in number of spawning salmon is more likely the result of repetitive counts, i.e., sampling error, of salmon moving within the basin during the 3-day spawning survey period.

Map 5. Holding distribution of salmon in the North Fork John Day River. Survey dates August 4-12, 1994.





Map 6. Holding distribution of salmon in Granite Creek and Clear Creek. Survey dates July 24-29 (Granite Creek), July 23-24 (Clear Creek) 1994.



Map 7. Holding distribution of salmon in the Middle Fork John Day River. Survey dates July 12-16, 1994.

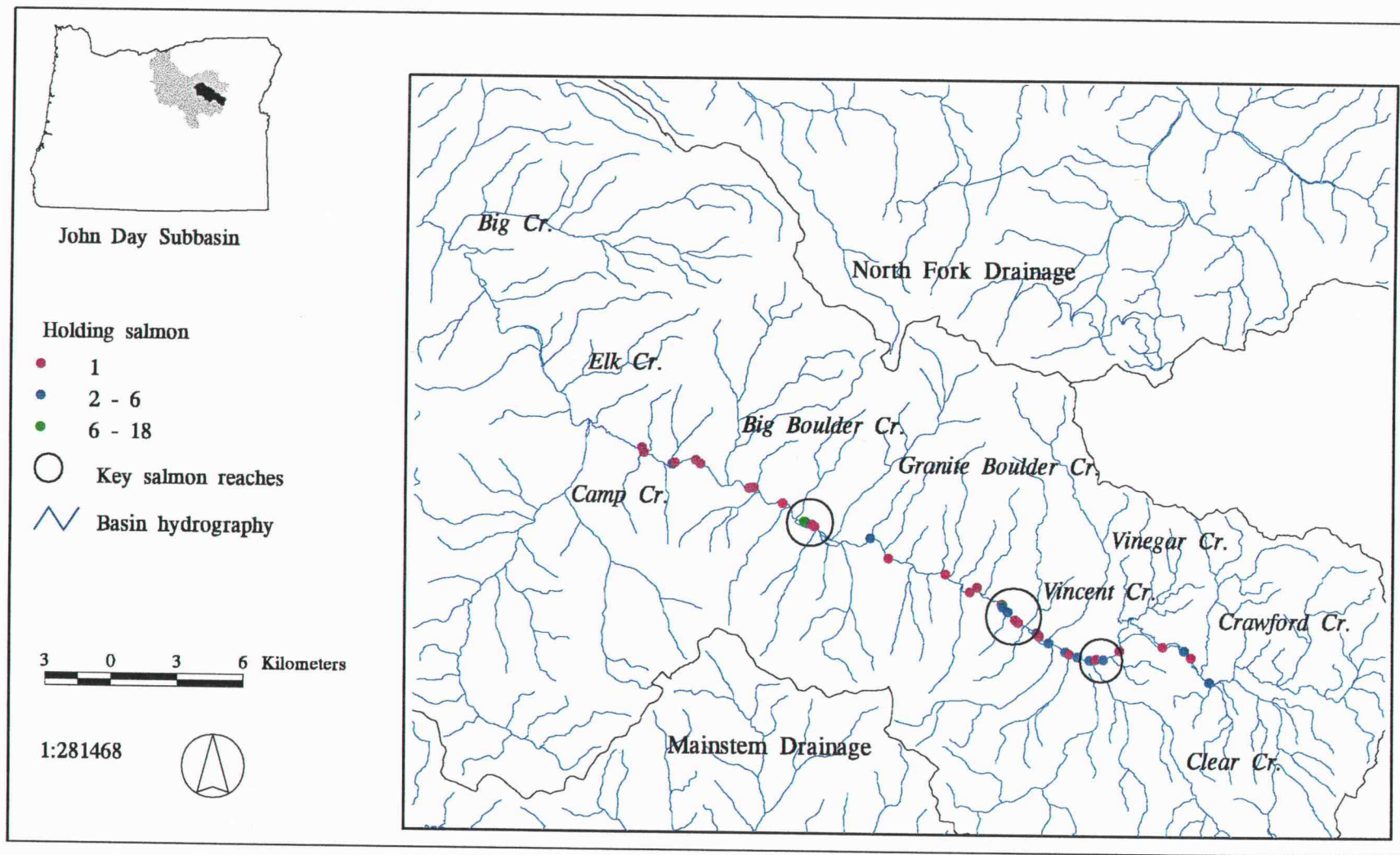


Table 6. Holding and spawning surveys of spring chinook salmon in the North Fork and Middle Fork John Day River, and Granite Creek/Clear Creek (North Fork subbasin) in 1994.

Salmon	John Day River subbasin		
	North Fork John Day River	Granite Creek, Clear Creek	Middle Fork John Day River
<i>Holding survey</i> <sup>a</sup>			
Survey reach (river km)	95-168	0-20	74-113
Number	302	111	92
On public land	301	85	13
On private land	1	26	79
Number/km	4.1	5.5	2.4
<i>Spawning survey</i> <sup>b</sup>			
Survey reach (river km)	no survey	0-20	74-113
Number	NA	145	116
On public land	NA	85	12
On private land	NA	60	104
Number/km	NA	7.3	3.0

<sup>a</sup> Diving survey conducted Aug. 4-12 (North Fork), and July 23-29 (Granite Cr. and Clear Cr.), July 12-16 (Middle Fork).

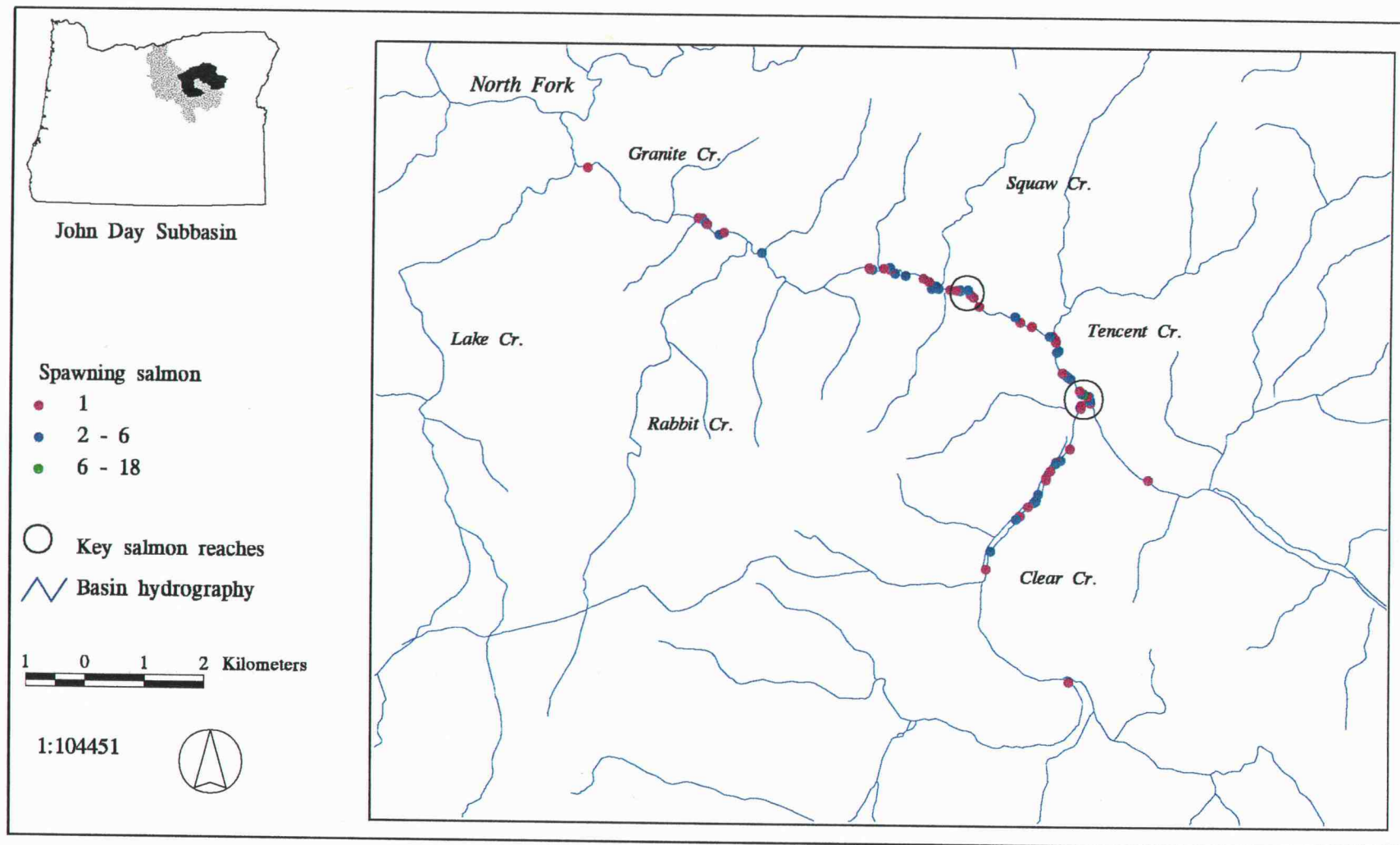
<sup>b</sup> Shore survey conducted Sept. 12-15 (Middle Fork), and Sept. 4-7 (Granite Cr. and Clear Cr.).

Table 7. Distribution of holding salmon in individual channel units in the North Fork and Middle Fork John Day River, and Granite Creek/Clear Creek (North Fork subbasin). Numbers of salmon are summarized according to within-unit density classes (salmon/unit).

Unit density class (salmon/unit)	North Fork John Day River			Granite Creek, Clear Creek			Middle Fork John Day River		
	No. of salmon	No. of units	Percent of total	No. of salmon	No. of units	Percent of total	No. of salmon	No. of units	Percent of total
1	53	53	18	20	20	18	35	35	38
2	32	16	11	10	5	9	16	8	17
3	24	8	8	3	1	3	6	2	7
4	8	2	3	-	-	-	-	-	-
5	10	2	3	10	2	9	10	2	11
6	12	2	4	6	1	5	6	1	7
7	14	2	5	-	-	-	7	1	8
8	16	2	5	-	-	-	-	-	-
10	20	2	7	-	-	-	-	-	-
12	12	1	4	12	1	11	12	1	13
13	13	1	4	-	-	-	-	-	-
14	28	2	9	-	-	-	-	-	-
17	17	1	6	-	-	-	-	-	-
19	19	1	6	-	-	-	-	-	-
24	24	1	8	-	-	-	-	-	-
50	-	-	-	50 <sup>a</sup>	1	45	-	-	-
Total	302	96	100	111	30	100	92	50	100

<sup>a</sup> Estimation on number of salmon holding in one large, deep (3 m) pool.

Map 8. Spawning distribution of salmon in Granite Creek and Clear Creek. Survey dates Sept. 4 (Clear Cr.), Sept. 7 (Granite Cr.).





Map 9. Spawning distribution of salmon in the Middle Fork John Day River. Survey dates Sept. 12-15, 1994.

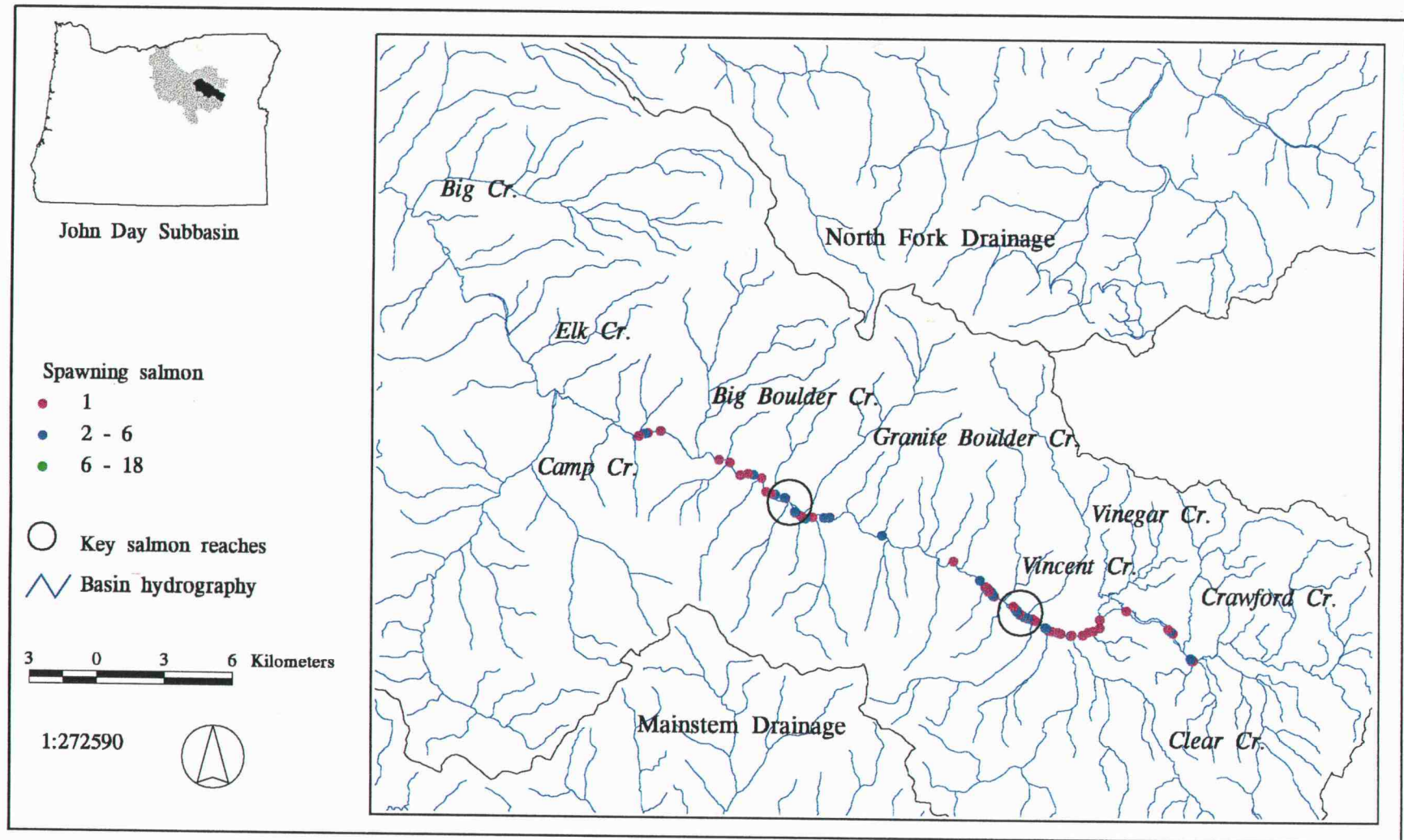


Table 8. Distribution of salmon during the late-spawning phase in individual channel units in the Middle Fork John Day River and Granite Creek/Clear Creek (North Fork subbasin). Numbers of salmon are summarized according to within-unit density classes (salmon/channel unit).

Unit density class (salmon/unit)	Granite Creek, Clear Creek			Middle Fork John Day River		
	No. of salmon	No. of units	Percent of total	No. of salmon	No. of units	Percent of total
1	39	39	27	46	46	40
2	34	17	23	30	15	26
3	45	15	31	27	9	23
4	8	2	6	8	2	7
5	5	1	3	5	1	4
6	6	1	4	-	-	-
8	8	1	6	-	-	-
Total	145	76	100	116	73	100

### Stream Habitat

Riffles were the dominant stream habitat type present in the North Fork, Middle Fork and Granite Creek/Clear Creek study reaches (Table 9). However, pools were the habitat most commonly utilized by spring chinook salmon. Holding and spawning salmon in all three study areas preferred pools over riffles and glides (Table 10). Electivity for pool habitats was highest in the Middle Fork, where depth was often the only form of cover. Seventy-eight percent of total pool area in the Middle Fork study reach was concentrated in low gradient alluvial valleys. Riffle use by holding salmon was highest in the North Fork (17%) compared to the other subbasins (1%); however, salmon in the Middle Fork and Granite Creek/Clear Creek increased their selection of riffles and glides after they initiated spawning and water temperatures had decreased (Tables 9 and 10). The longitudinal distribution of pool density in the North Fork, Middle Fork, and Granite Creek/Clear Creek exhibited clustered patterns and appeared to be associated with key salmon holding areas (Maps 10, 11, and 12).

Table 9. Stream habitat availability and use by spring chinook salmon the North Fork and Middle Fork John Day River and Granite Creek (North Fork subbasin). The North Fork was surveyed in Sept. 1994 from river kilometer 95-168. Granite Creek was surveyed in Sept. 1994 from river kilometer 0-12.6. The Middle Fork was surveyed in Oct. 1993 from river kilometer 62-113. Summary habitat data represent only primary channels. Mean channel dimensions are depicted with standard errors in parentheses. Habitat use was determined from spawning and holding surveys conducted in 1994.

Stream habitat <sup>a</sup>	John Day River subbasin		
	North Fork John Day River	Granite Creek <sup>b</sup>	Middle Fork John Day River <sup>c</sup>
<i>Pools</i>			
Total area (m <sup>2</sup> )	204,876	52,181	52,193
Total number	457	117	160
On public land (%)	95	65	22
On private land (%)	5	35	78
Area / km	3,201	2,609	1535
Average maximum depth (m)	0.84 (0.01)	1.08 (0.04)	0.87 (0.03)
Average depth (m)	0.46 (0.01)	0.53 (0.02)	0.41 (0.01)
Average volume (m <sup>3</sup> )	182 (11)	258 (28)	114 (7)
Habitat availability (%)	20	38	13
Habitat use, holding salmon (%)	82	98	98
Habitat use, spawning salmon (%)	NA	69	83
<i>Riffles</i>			
Total area (m <sup>2</sup> )	736,491	74,855	262,948
On public land (%)	100	90	23
On private land (%)	0	10	77
Area / km	11,508	3,743	7,734
Average depth (m)	0.23 (0.00)	0.18 (0.01)	0.22 (0.00)
Average volume (m <sup>3</sup> )	384 (62)	125 (32)	203 (21)
Habitat availability (%)	72	54	65
Habitat use, holding salmon (%)	17	1	1
Habitat use, spawning salmon (%)	NA	26	13
<i>Glides</i>			
Total area (m <sup>2</sup> )	81,396	11,025	86,386
On public land (%)	81	85	28
On private land (%)	19	15	72
Area / km	1,272	551	2,541
Average depth (m)	0.34 (0.01)	0.27 (0.01)	0.31 (0.01)
Average volume (m <sup>3</sup> )	278 (27)	78 (7)	129 (9)
Habitat availability (%)	8	8	22
Habitat use, holding salmon (%)	1	1	1
Habitat use, spawning salmon (%)	NA	5	4

<sup>a</sup> Habitat surveys were conducted after Hankin and Reeves (1988).

<sup>b</sup> Habitat survey does not include Clear Creek.

<sup>c</sup> Middle Fork estimates of channel unit volume are not directly comparable to North Fork and Granite Creek due to different survey years.

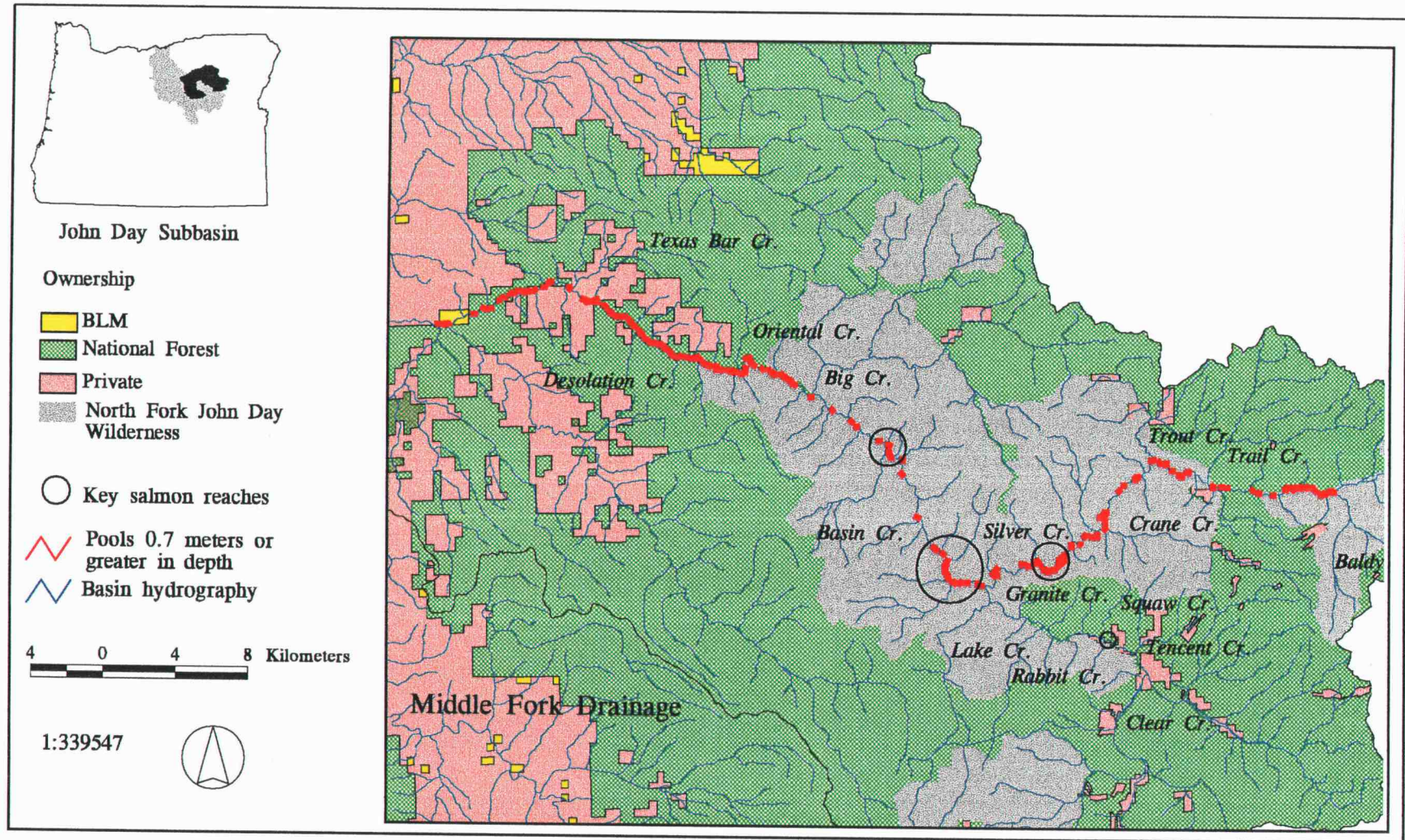


Table 10. Stream habitat electivity indices for spring chinook salmon in the North Fork and Middle Fork John Day River, and Granite Creek. Indices show relative preference (positive values) and avoidance (negative values) of stream habitat types during holding and spawning phases.

Habitat type	North Fork John Day River		Granite Creek		Middle Fork John Day River	
	Holding	Spawning	Holding	Spawning	Holding	Spawning
<i>Electivity</i> <sup>a</sup>						
pool	0.61	NA	0.44	0.29	0.77	0.73
riffle	-0.62	NA	-0.96	-0.35	-0.97	-0.67
glide	-0.78	NA	-0.78	-0.23	-0.91	-0.69

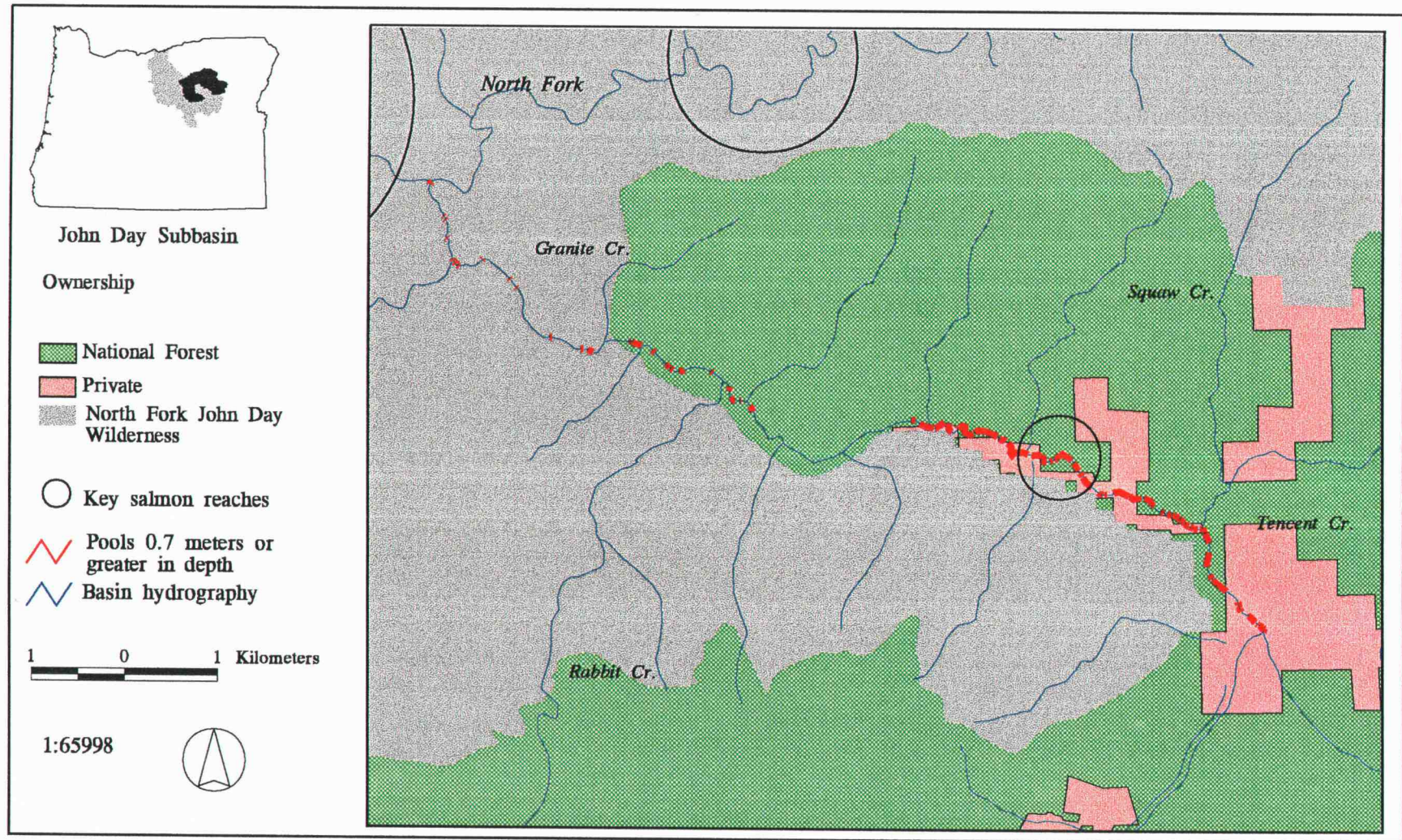
<sup>a</sup> Ivlev's electivity index  $(P_u - P_a) / (P_u + P_a)$ , where  $P_u$  is the proportion of resource used, and  $P_a$  is the proportion of the resource available. The index ranges from -1 and approaches +1; negative values suggest avoidance and positive values suggest election (Manly et al. 1993).

Map 10. Land ownership and pools in the North Fork John Day River study reach.



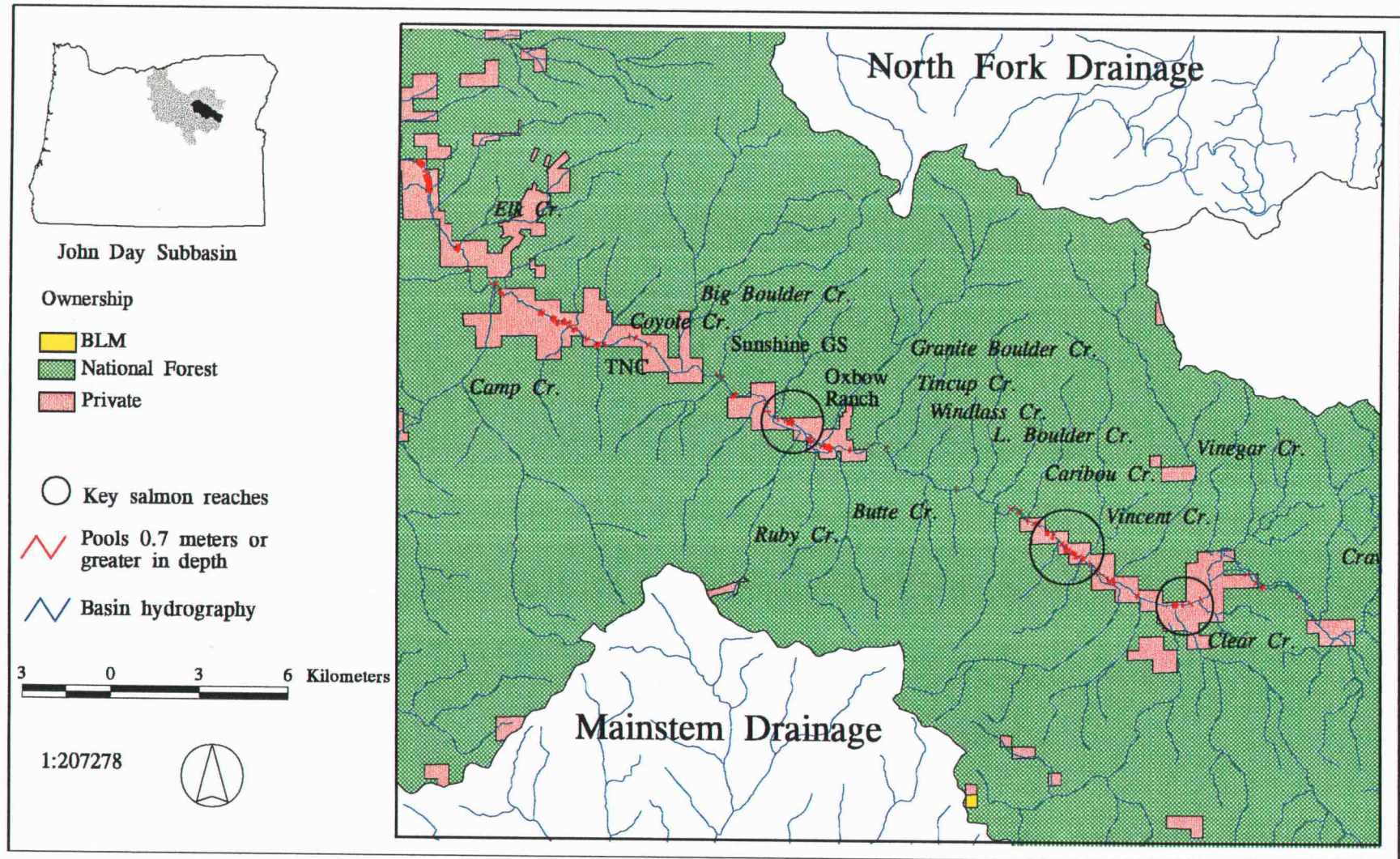


Map 11. Land ownership and pools in the Granite Creek study reach.





Map 12. Land ownership and pools in the Middle Fork John Day River study reach.





### Stream Temperature

Stream temperature patterns in the North Fork, Middle Fork, and Granite Creek/Clear Creek showed general warming trends in the downstream direction punctuated by cool and warm anomalies (Maps 13 and 14). Anomalies in the downstream warming trend in the North Fork study reach occurred both upstream of Big Creek and downstream of Crane Creek. The reach downstream of Crane Creek passes southwesterly through a forest burn site where topographic and riparian shading is limited. Another warm-water anomaly with an approximate 2°C increase was located in the upper reaches of Clear Creek where, due to low flow conditions, the stream alternately flowed above and below the stream bed, leaving interspersed warm pools isolated from hyporheic inputs (Map 13).

The directional warming trend in the Middle Fork study reach was not as distinct as that in the North Fork, and overall maximum reach temperatures were higher in the Middle Fork, even after accounting for daily temperature differences between survey dates (Table 2). Downstream from the spring-fed headwater reach near Crawford Creek, stream temperatures in the longitudinal profile increased dramatically by 3-4°C, after which relative cooling occurred in the low gradient reach from Vinegar Creek to Little Boulder Creek and, again, near Ruby Creek. Downstream from Elk Creek, water temperature decreased slightly as the river passes through a historic mining reach containing deep (1-1.5 m) pools situated among extensive dredge tailings. Downstream of the mining reach, temperature rose to 26-27°C and remained relatively constant from Big Creek to the lower boundary of the thermal survey at Indian Creek.

Surface water inputs, such as tributary confluences, seeps, and irrigation inflow, were more numerous per river kilometer in the Middle Fork compared to Granite Creek (Table 11). Remnant side-channel and streambank seeps were the most common surface water inputs in both study reaches. We found it difficult, however, in the Middle Fork to differentiate between seeps of natural origin and irrigation-related inflow because canals cut extensively along upslope contours and across the flood plain in alluvial valleys. Surface water inputs classified during surveys as natural seeps exhibit distinctly clustered patterns, especially in the Middle Fork (Maps 15 and 16). Reaches with particularly high

concentrations of seeps were located just downstream of Crawford Creek and also below Ruby Creek in the Middle Fork. Other localized patches of seeps were distributed throughout low and high gradient reaches in both streams. Mean seep temperature, in relation to main channel temperature, was  $1.5 \pm 0.5^{\circ}\text{C}$  degrees cooler in Granite Creek/Clear Creek than in the Middle Fork (unpaired t-test,  $p < 0.01$ ). The coldest seeps in the Middle Fork and Granite Creek/Clear Creek, respectively, were  $13^{\circ}$  and  $9^{\circ}\text{C}$  colder than the main channel.

Table 11. Summary of surface water inputs classified by type in Granite Creek/Clear Creek (North Fork subbasin) and the Middle Fork John Day River. Surveys were conducted in September 1994.

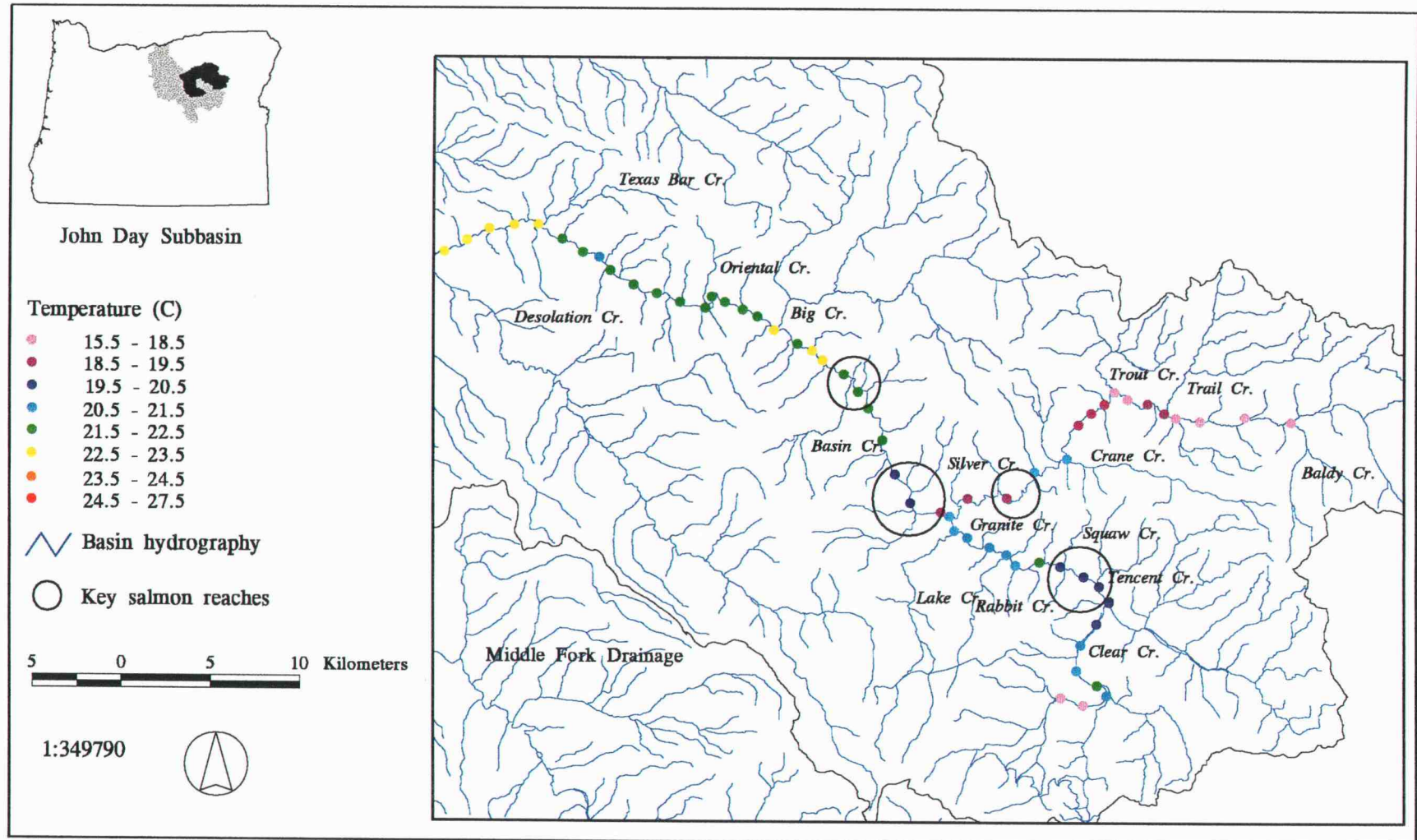
Input type	Granite Creek, Clear Creek	Middle Fork John Day River
Tributaries	14	27
Seeps <sup>a</sup>	46	149
Pond seeps <sup>b</sup>	1	4
Irrigation seeps <sup>c</sup>	0	30
Total	61	210
Number/km	3.1	4.9
Survey reach (river km)	0-20	74-113

<sup>a</sup> Includes remnant side-channel and streambank seeps.

<sup>b</sup> Seeps originating in cut-off meander and spring-fed ponds.

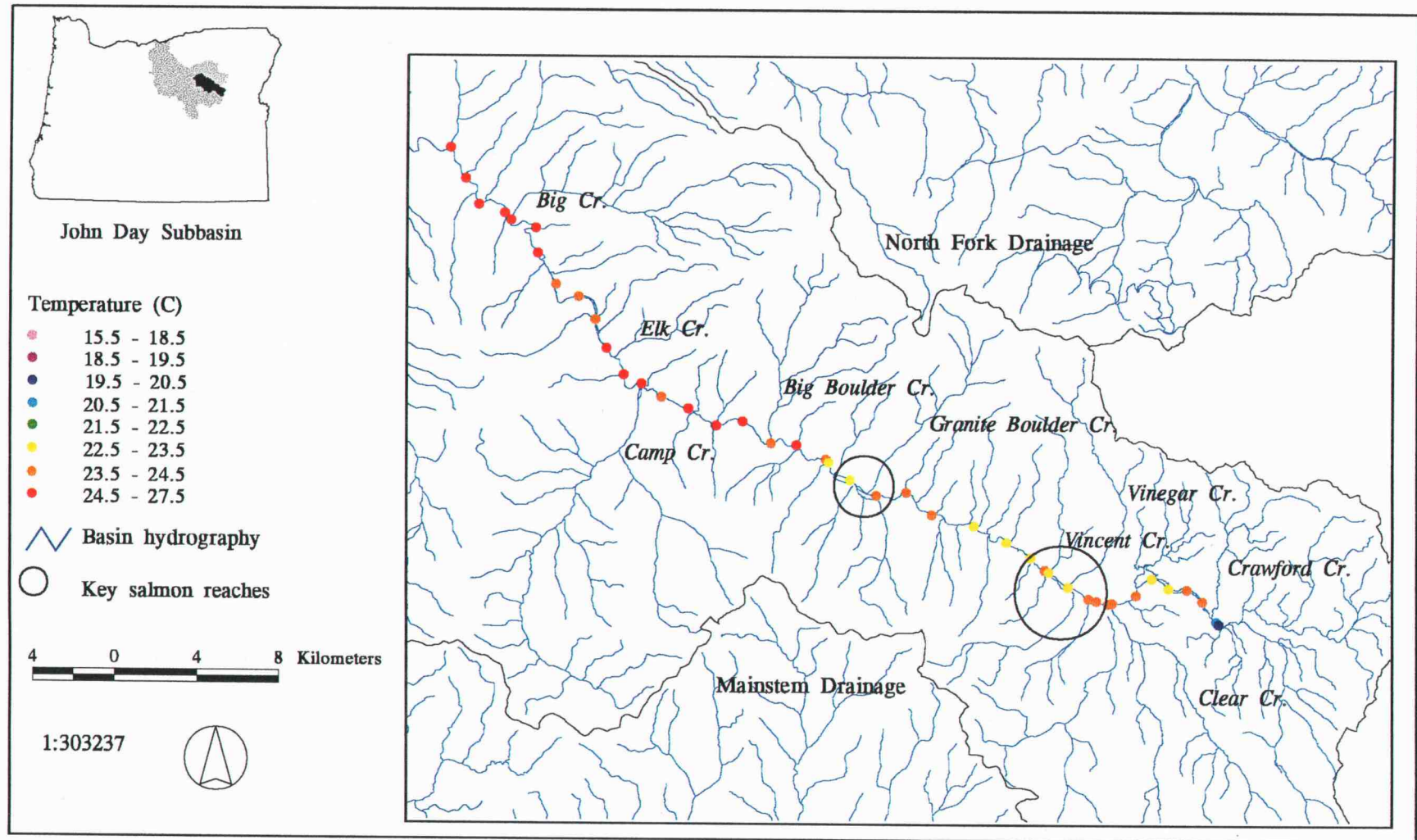
<sup>c</sup> Surface water inputs ostensibly related to irrigation return flow.

Map 13. Longitudinal temperature profile of the North Fork John Day River study reach, August 8, 1994 (1400 - 1600 hr).



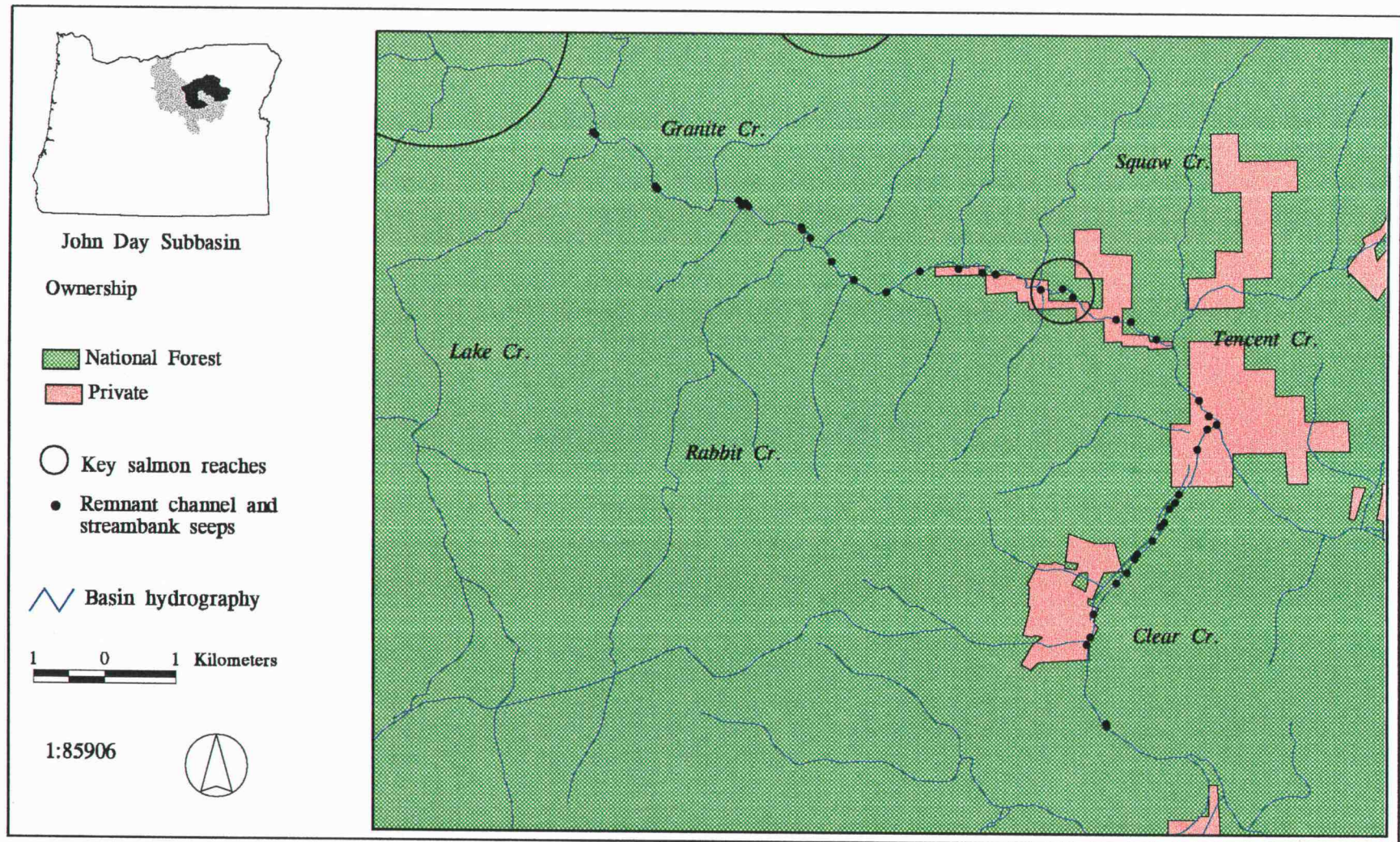


Map 14. Longitudinal temperature profile of the Middle Fork John Day River study reach, August 5, 1994 (1400-1500 hr).



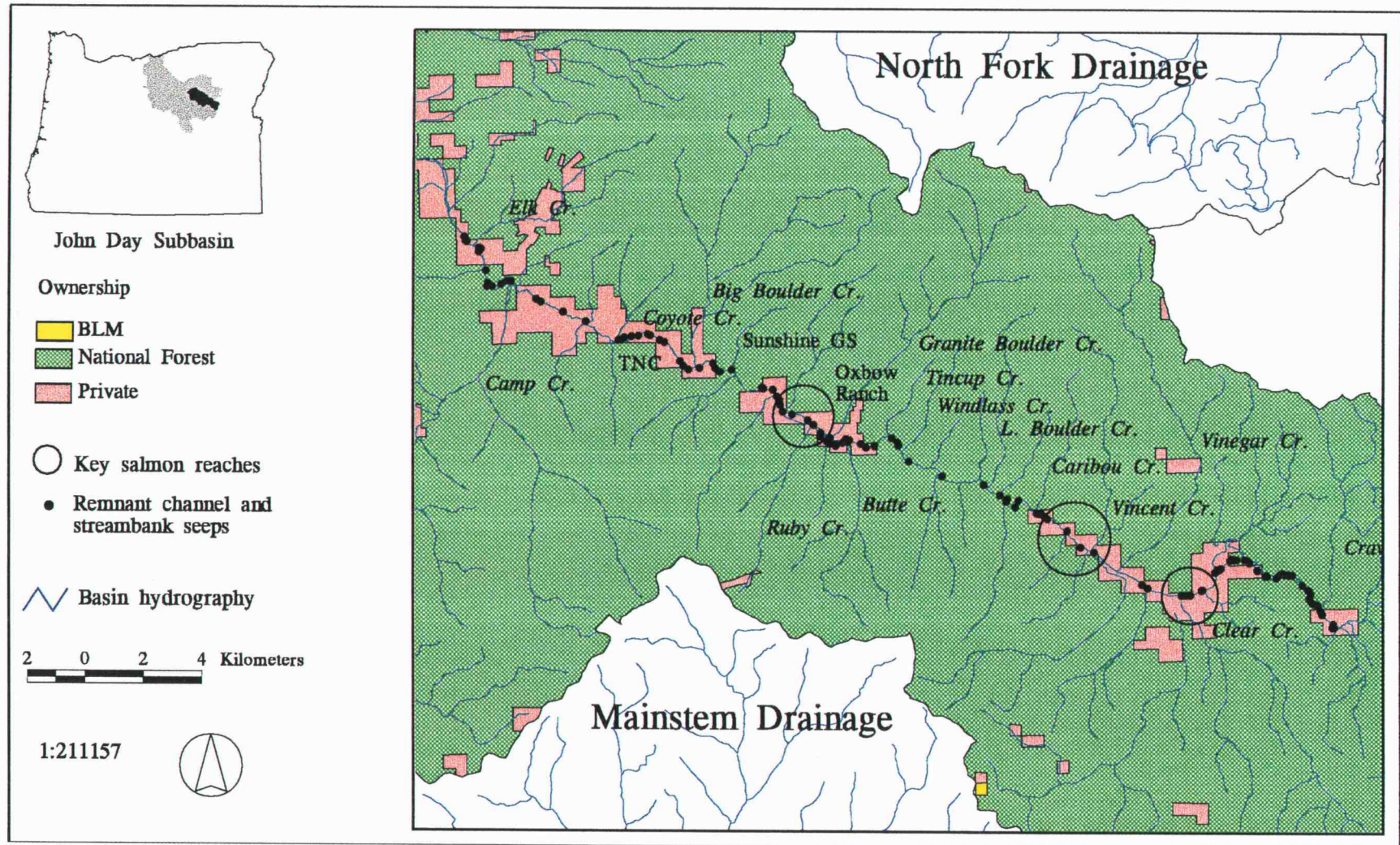


Map 15. Seeps and land ownership in Granite Cr. and Clear Cr. study reaches.





Map 16. Seeps and land ownership in the Middle Fork John Day River study reach.



## Spatial Analysis

### Channel and Subunit Patterns

Thermal image mosaics of selected 2-3 km reaches in the North Fork, Granite Creek, and Middle Fork served as the basis for small-scale thermal pattern analysis. Within each subbasin, we selected two reaches to examine in detail: (1) a reach with high densities of holding salmon, and (2) a reach with low densities of salmon. In the North Fork and Granite Creek, low density reaches were selected in relatively warmer, downstream habitats. In the Middle Fork, we examined both cool (upstream) and warm (downstream) reaches containing low densities of holding salmon. The images in the following figures were selected as representative subsections from larger thermal image mosaics, and their respective geographic locations are shown in Map 17. The spatial progression of images in Figures 4 through 15 is downstream to upstream for each respective subbasin.

The lower North Fork reach, flowing southwesterly from Texas Bar Creek downstream to the lower boundary of the study reach, is characterized by shallow riffles interspersed with gradient breaks and mid-channel pools (depth > 0.7 m) created by boulders. Only one salmon, located in a pool just downstream of a rapid, was observed in this reach during the August survey of holding salmon (Figure 4). At mid-afternoon during the thermal survey, stream temperature in this reach maintained a constant thalweg temperature of 22°C for 2 km. Overall, stream temperature was constant within and among channel units, with little evidence of groundwater exchange with the main channel.

In the North Fork wilderness reach approximately 30 km upstream of the Texas Bar Creek site, we observed many salmon holding both in riffles and in pools (Figure 5). Stream temperature throughout the reach was several degrees cooler than temperatures in the lower North Fork, and rarely varied more than 1°C. Although salmon showed a strong preference for depth as a cover type (e.g., one large pool contained 21 salmon), they were not found exclusively in pools. Several kilometers downstream of the Granite Creek confluence, we observed more salmon holding in riffles and rapids (Figure 6). Some cool-

water areas, such as tributary confluences, were apparent in the imagery, but they were not used by salmon because the confluence habitats were too shallow. During the thermal survey, the forested canyon walls depicted in Figure 6 forced the helicopter to fly higher, thereby reducing the spatial resolution of the imagery. This may have affected our ability to detect small cool-water areas, especially where the channel was narrow and interspersed with boulders, which cause thermal interference.

Granite Creek is a major tributary of the North Fork that flows from the confluence with Clear Creek through a low gradient reach of extensive dredge tailings and then passes through a high gradient, canyon reach before entering the North Fork. The principal holding and spawning areas are located in the upper, unconstrained valley between Clear Creek and Squaw Creek. In the low gradient reaches, off-channel ponds, formed among piles of dredged bed material, may contribute subsurface flow to the main channel. We observed the greatest thermal heterogeneity among channel units in the low gradient reaches of Granite Creek near the confluence with Tencent Creek. Stream temperature in Granite Creek varied on the order of  $1^{\circ}\text{C}$  within individual pools and  $1\text{--}3^{\circ}\text{C}$  in riffle-pool sequences. Water temperature was approximately  $2^{\circ}\text{C}$  warmer in downstream reaches (Figure 7) compared to reaches 5 km upstream (Figures 8 and 9). In contrast to the North Fork, salmon holding in Granite Creek frequently occupied habitats that were  $1^{\circ}\text{C}$  cooler than the immediately surrounding habitat (Figures 7-9). However, the salmon showed particular preference for one large, relatively cold pool near Squaw Creek (Figure 8) where they congregated in numbers upwards of 50 individuals, leaving other upstream cool habitats unoccupied (Figure 9).

Maximum daily stream temperatures were highest in the lower Middle Fork near Big Creek compared to the North Fork and Granite Creek study reaches, even after accounting for differences in survey date (Table 2). We expected the lower Middle Fork reach to be homogeneously warm; however, we noted a consistent  $1^{\circ}\text{C}$  difference between shallow riffles and slightly deeper habitats (Figure 10). These observations may indicate the importance of channel width-to-depth ratio as a factor influencing small-scale stream temperature changes in this particular reach. The lack of salmon in the Big Creek reach of

the Middle Fork possibly is explained by several habitat-related factors, such as insufficient cover and depth, in addition to high summer water temperatures.

In the major holding and spawning reaches of the Middle Fork, approximately 40 km upstream of Big Creek, water temperatures were at least 3-4°C cooler. Salmon frequently, but not exclusively, occupied subunit positions that were 1-2°C cooler than the immediately surrounding habitat. One group of 12 individuals (including one radio-tagged salmon) held over summer in a pool with large, relatively cooler patches (Figure 11). The two radio-tagged salmon that oversummered in this reach both occupied channel units containing cool-water patches (Price 1996). Cool-water areas were frequently pools, which were the habitat most preferred by salmon (Table 10).

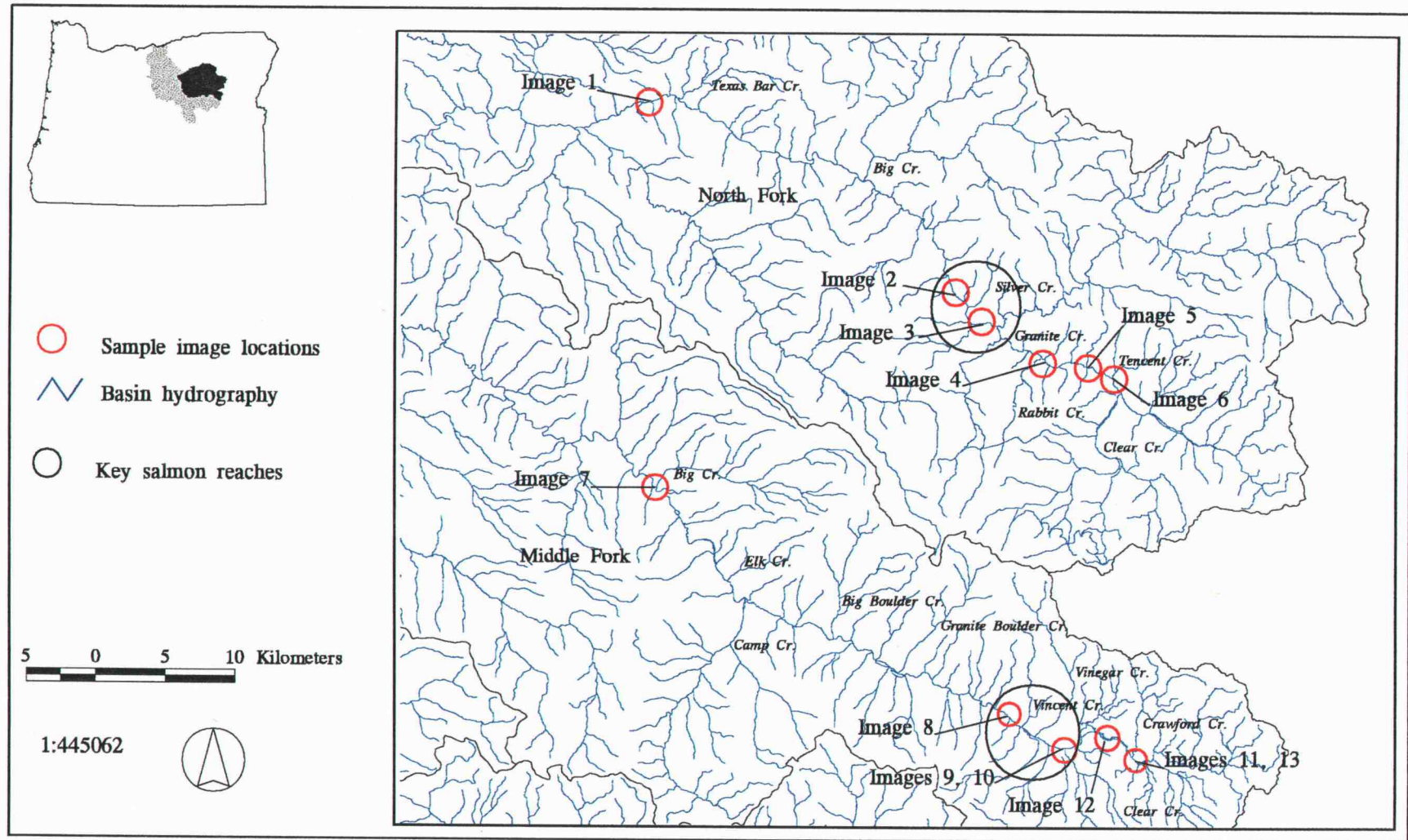
Several salmon were associated with the relatively cool confluence of Clear Creek, but we did not observe any salmon actually holding in the coldest region of the plume because it was less than 15 cm in depth (Figure 12). The locations of salmon superimposed on the imagery indicate the location of a salmon when it was sighted by the diver. In some cases, the salmon were mapped in unlikely locations because they were disturbed before they were sighted. Such was the case in Figure 12, in which a salmon was taking cover from the diver upstream of the cool confluence plume. In instances such as these, the observer on shore was able to trace the movement of the salmon from its original location. Approximately 200 meters upstream of the Clear Creek confluence, we observed 5 more salmon holding in a pool that appeared approximately 1-2°C warmer than habitats downstream of the confluence (Figure 13). Within the pool, however, salmon were located in a microhabitat that was slightly cooler than adjacent habitats. The warm water surrounding this group of salmon may have restricted their exploratory efforts to locate cooler habitats.

We observed only two salmon holding in the uppermost headwaters of the Middle Fork (Figure 14). This cool-water reach is grazed periodically but not currently irrigated, and channel morphology has not been significantly altered. Several groundwater springs on the west side of the unconstrained river valley combine and contribute more than half of the flow to the main channel of the Middle Fork (Figure 15). The two salmon found in this reach were located among cool-water patches associated with direct groundwater flow

through the stream bank (Figure 14). The flow of groundwater through cut-off meanders and other subsurface pathways is recognizable (dark red color) in the thermal image as an area of increased soil moisture, i.e., increased emissivity. Other examples of groundwater seeps (Image 12) and headwater springs (Image 13) are displayed in Figure 15.



Map 17. Sample thermal image locations in the North Fork and Middle Fork John Day River study reaches.



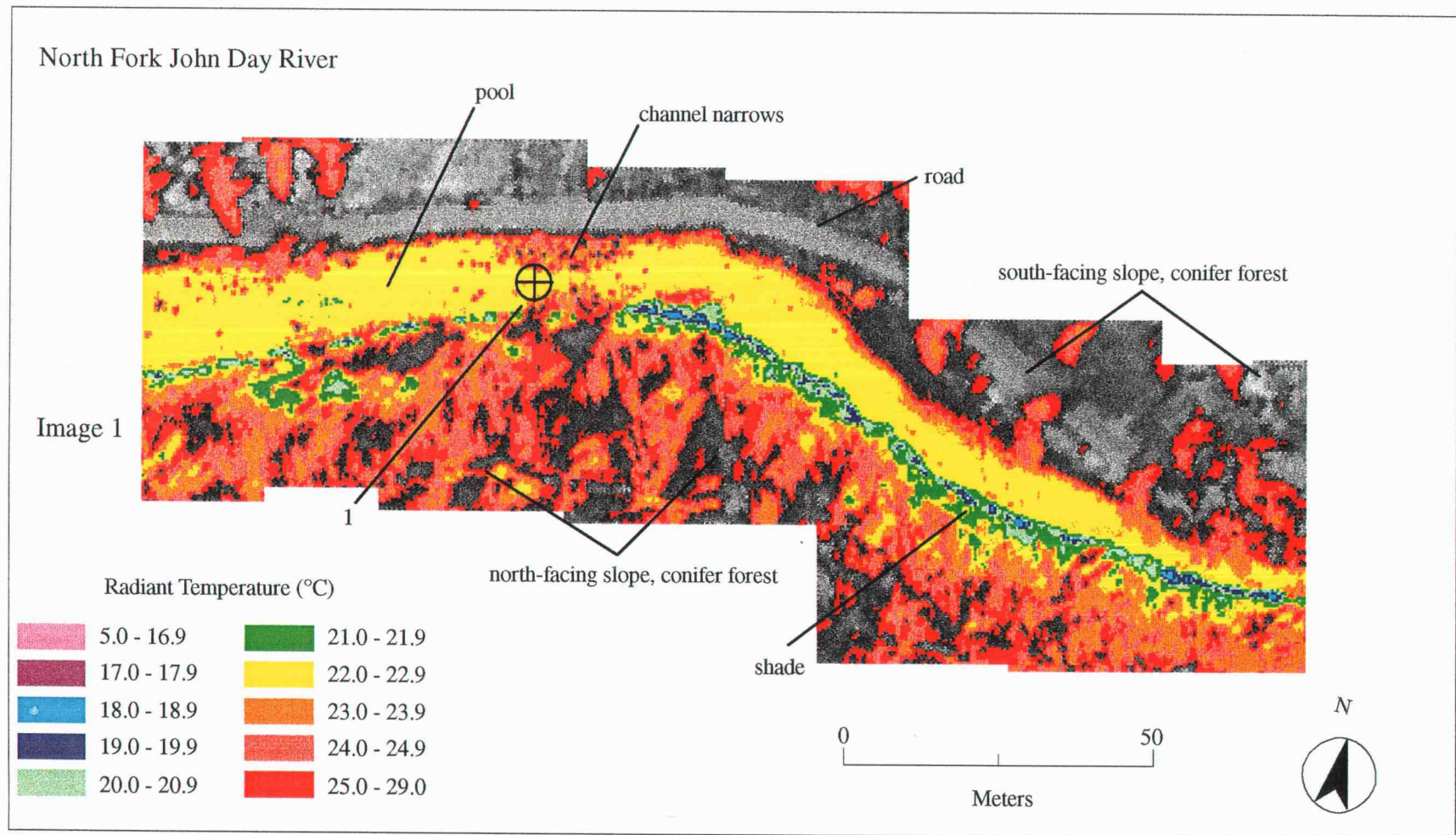


Figure 4. Thermal image (1) of the lower North Fork John Day River. The black circle shows the approximate location of a holding salmon. Numbers in the margins indicate the number of salmon observed in each location. Direction of flow is page right to page left. Temperatures greater than 29° C are shown in gray tones (lighter is hotter).



# North Fork John Day River

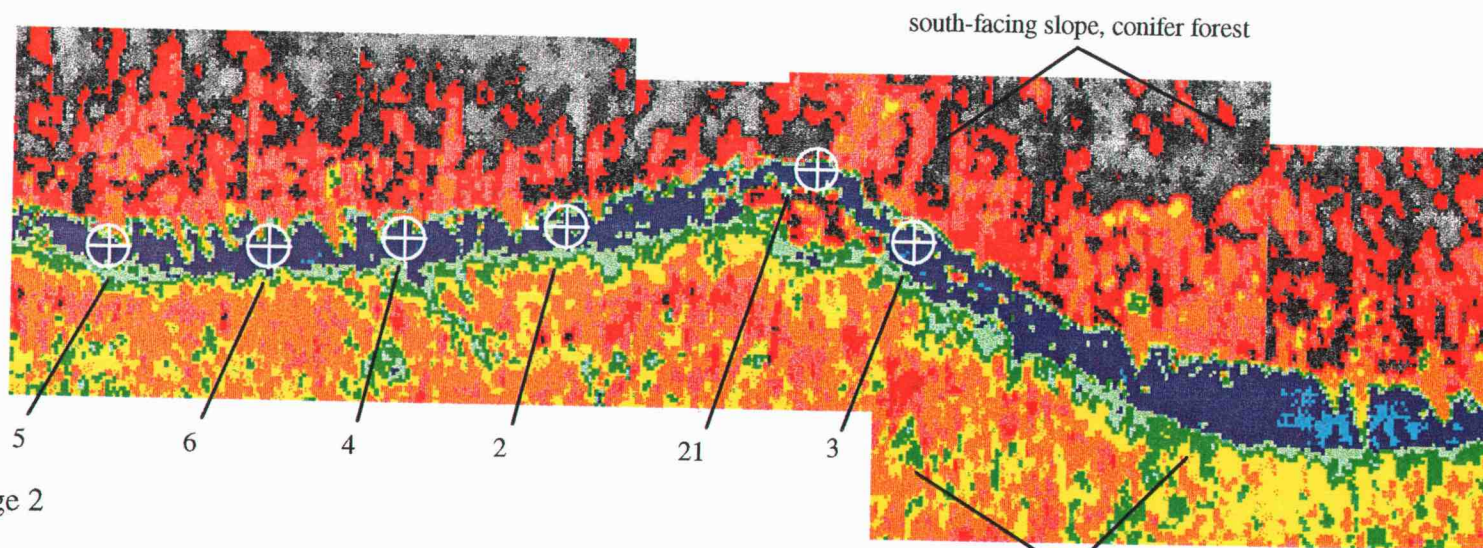


Image 2

Radiant Temperature (°C)

5.0 - 16.9	21.0 - 21.9
17.0 - 17.9	22.0 - 22.9
18.0 - 18.9	23.0 - 23.9
19.0 - 19.9	24.0 - 24.9
20.0 - 20.9	25.0 - 29.0

0 60  
Meters



Figure 5. Thermal image (2) of the North Fork John Day River wilderness reach. White circles show approximate locations of holding salmon. Numbers in the margins indicate the number of salmon observed in each location. Direction of flow is page right to page left. Temperatures greater than 29° C are shown in gray tones (lighter is hotter).

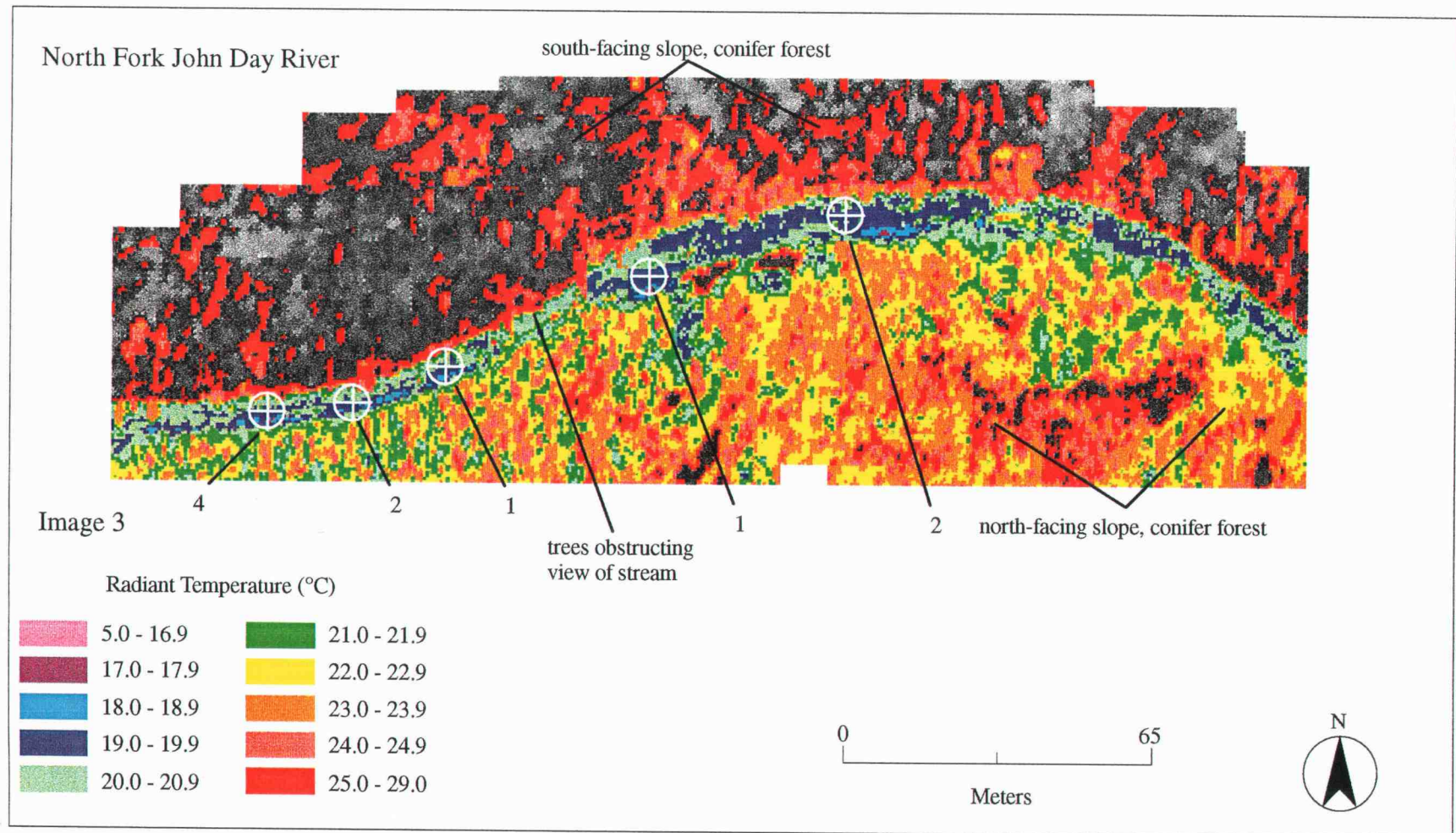


Figure 6. Thermal image (3) of the North Fork John Day River wilderness reach. Circles show approximate locations of holding salmon. Numbers in the margins indicate the number of salmon observed in each location. Direction of flow is page right to page left. Temperatures greater than 29° C are shown in gray tones (lighter is hotter).



# Granite Creek (North Fork subbasin)

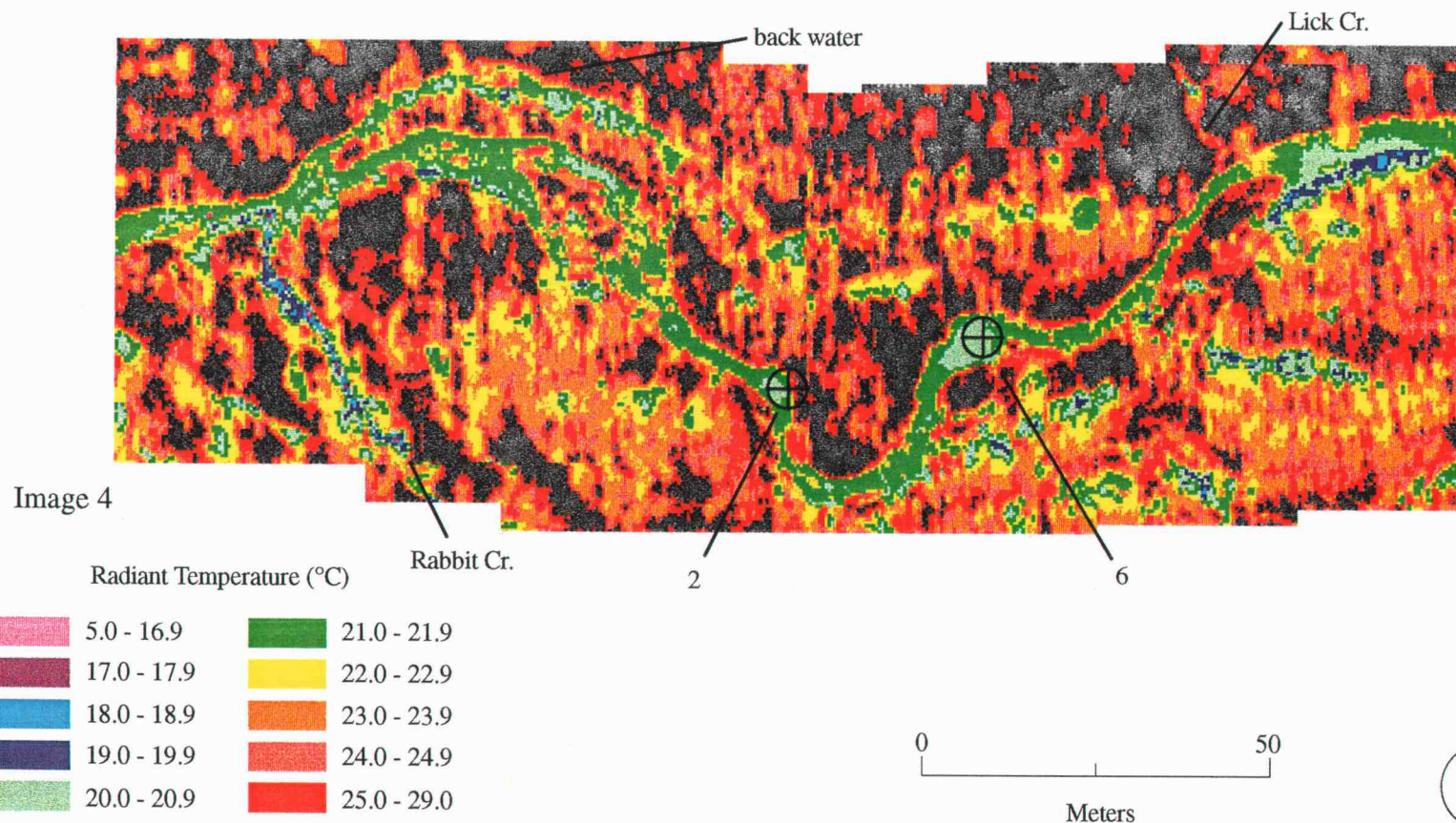
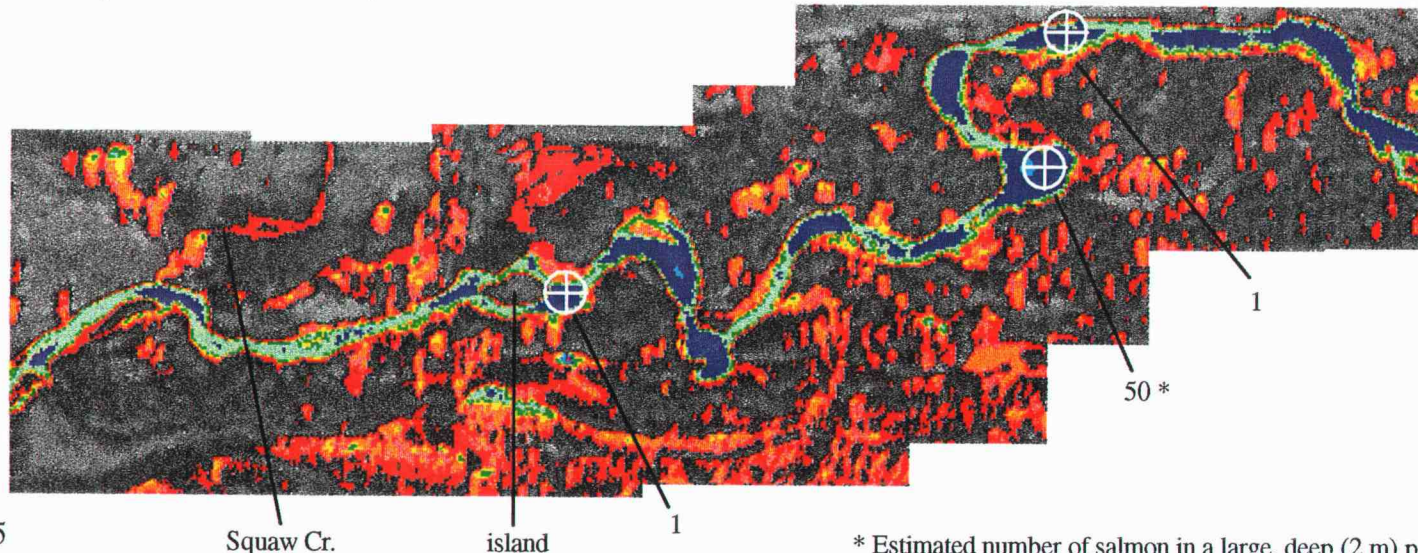


Figure 7. Thermal image (4) of Granite Creek, at Rabbit Creek. Black circles show approximate locations of holding salmon. Numbers in the margins indicate the number of salmon observed in each location. Direction of flow is page right to page left. Temperatures greater than 29° C are shown in gray tones (lighter is hotter).

# Granite Creek (North Fork subbasin)



## Radiant Temperature (°C)

5.0 - 16.9	21.0 - 21.9
17.0 - 17.9	22.0 - 22.9
18.0 - 18.9	23.0 - 23.9
19.0 - 19.9	24.0 - 24.9
20.0 - 20.9	25.0 - 29.0

0 60  
Meters



Figure 8. Thermal image (5) of Granite Creek, at Squaw Creek. White circles show approximate locations of holding salmon. Numbers in the margins indicate the number of salmon observed in each location. Direction of flow is page right to page left. Temperatures greater than 29° C are shown in gray tones (lighter is hotter).



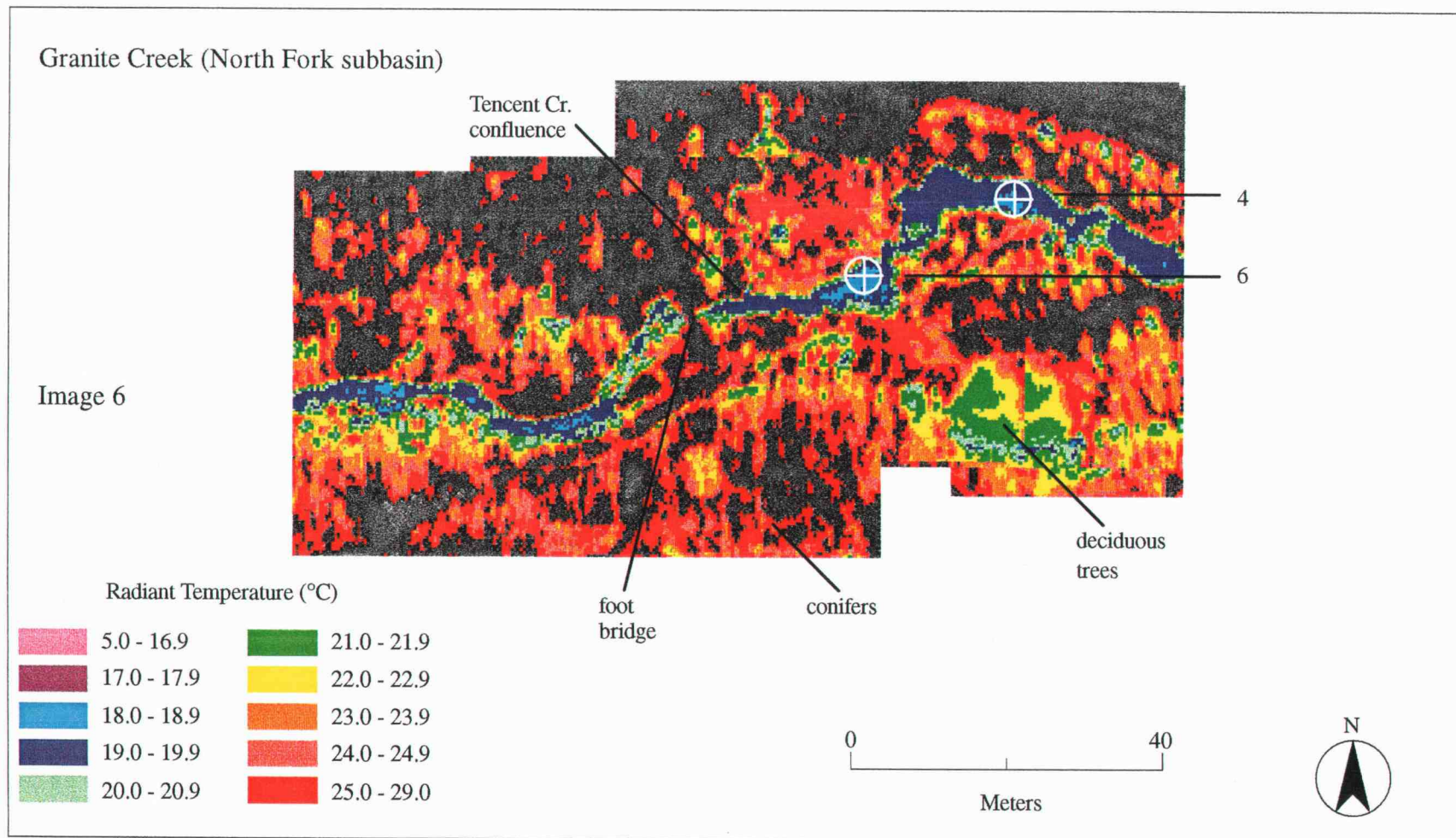
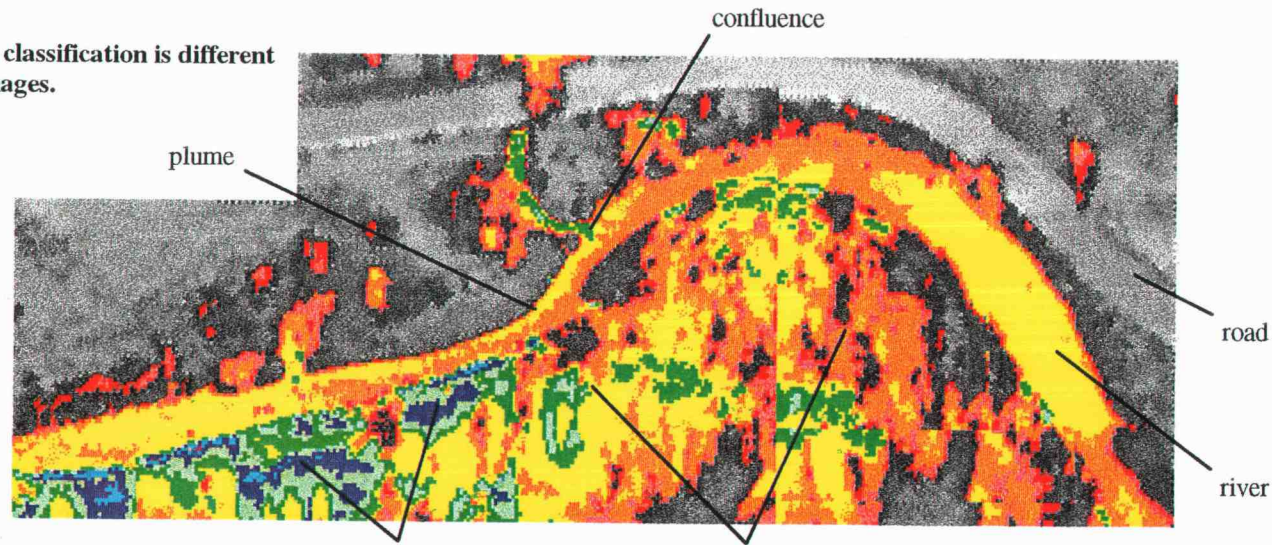


Figure 9. Thermal image (6) of Granite Creek, at Tencent Creek. Black circles show approximate locations of holding salmon. Numbers in the margins indicate the number of salmon observed in each location. Direction of flow is page right to page left. Temperatures greater than 29° C are shown in gray tones (lighter is hotter).

# Middle Fork John Day River

\* Note: temperature classification is different from preceding images.

Image 7



Radiant Temperature (°C) \*

20.0 - 20.9	25.0 - 25.9
21.0 - 21.9	26.0 - 26.9
22.0 - 22.9	27.0 - 27.9
23.0 - 23.9	28.0 - 28.9
24.0 - 24.9	29.0 - 30.0

0 50  
Meters



Figure 10. Thermal image (7) of the Middle Fork John Day River, at the Big Creek confluence with the main stem. Direction of flow is page right to page left. No salmon were observed in this reach. Black lines indicate the tributary confluence and the associated cool plume. Temperatures greater than 30° C are shown in gray tones (lighter is hotter).



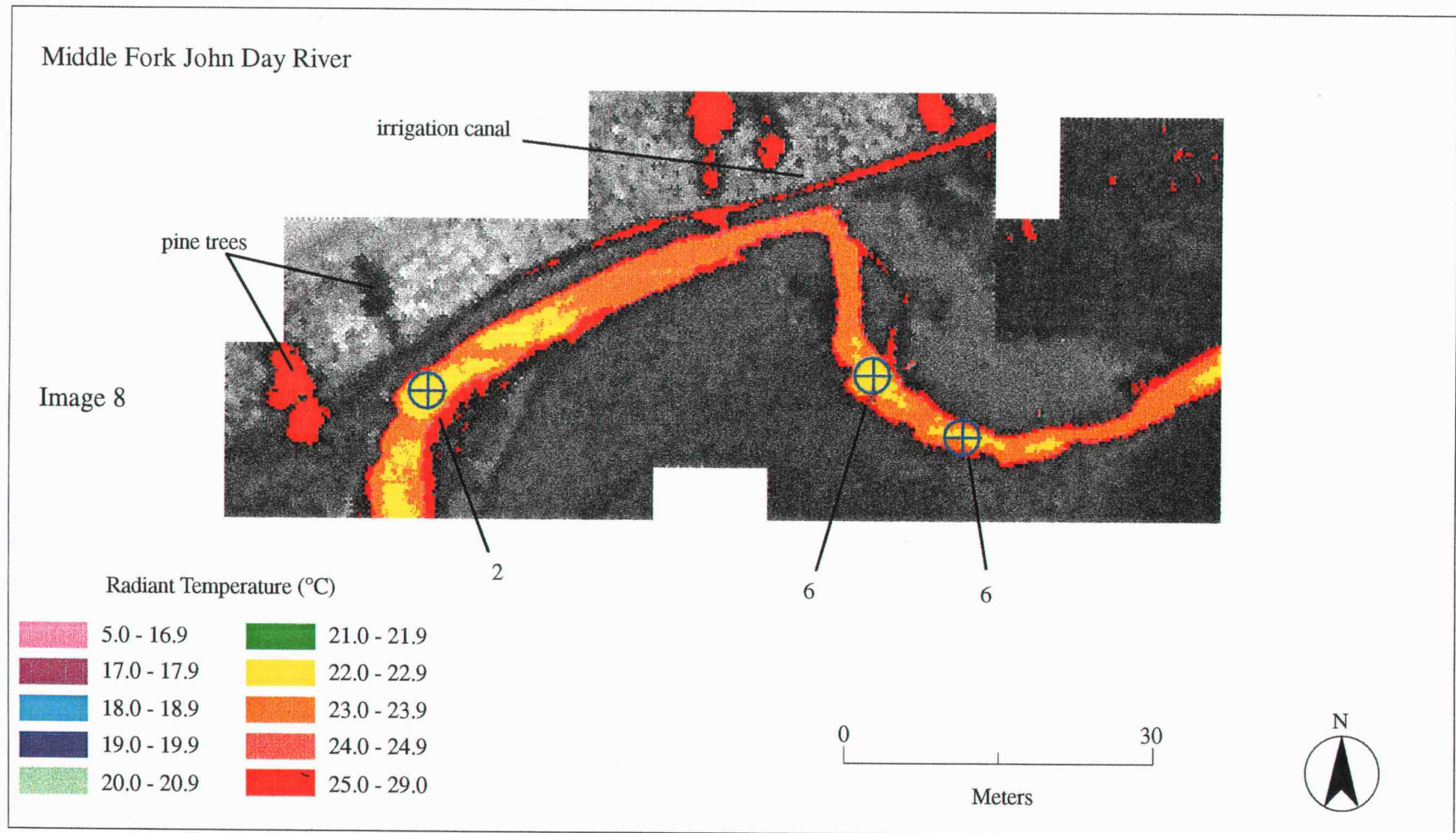


Figure 11. Thermal image (8) of the Middle Fork John Day River. Blue circles show approximate locations of holding salmon. Numbers in the margins indicate the number of salmon observed in each location. Direction of flow is page right to page left. Temperatures greater than 29° C are shown in gray tones (lighter is hotter).

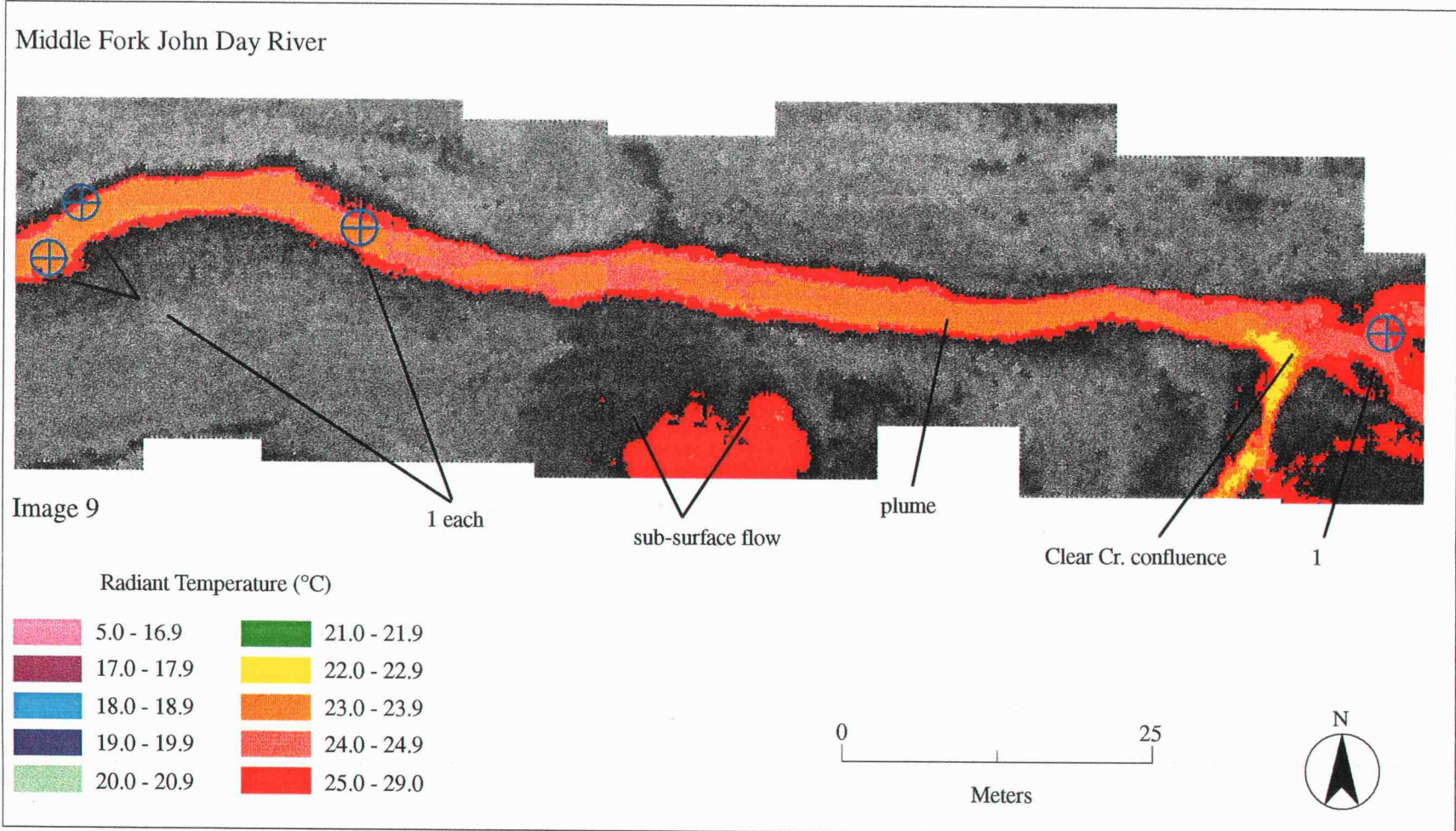


Figure 12. Thermal image (9) of the Middle Fork John Day River, at the Clear Creek confluence with the main stem. Blue circles show approximate locations of holding salmon. Numbers in the margins indicate the number of salmon observed in each location. Direction of flow is page right to page left. Temperatures greater than 29° C are shown in gray tones (lighter is hotter).



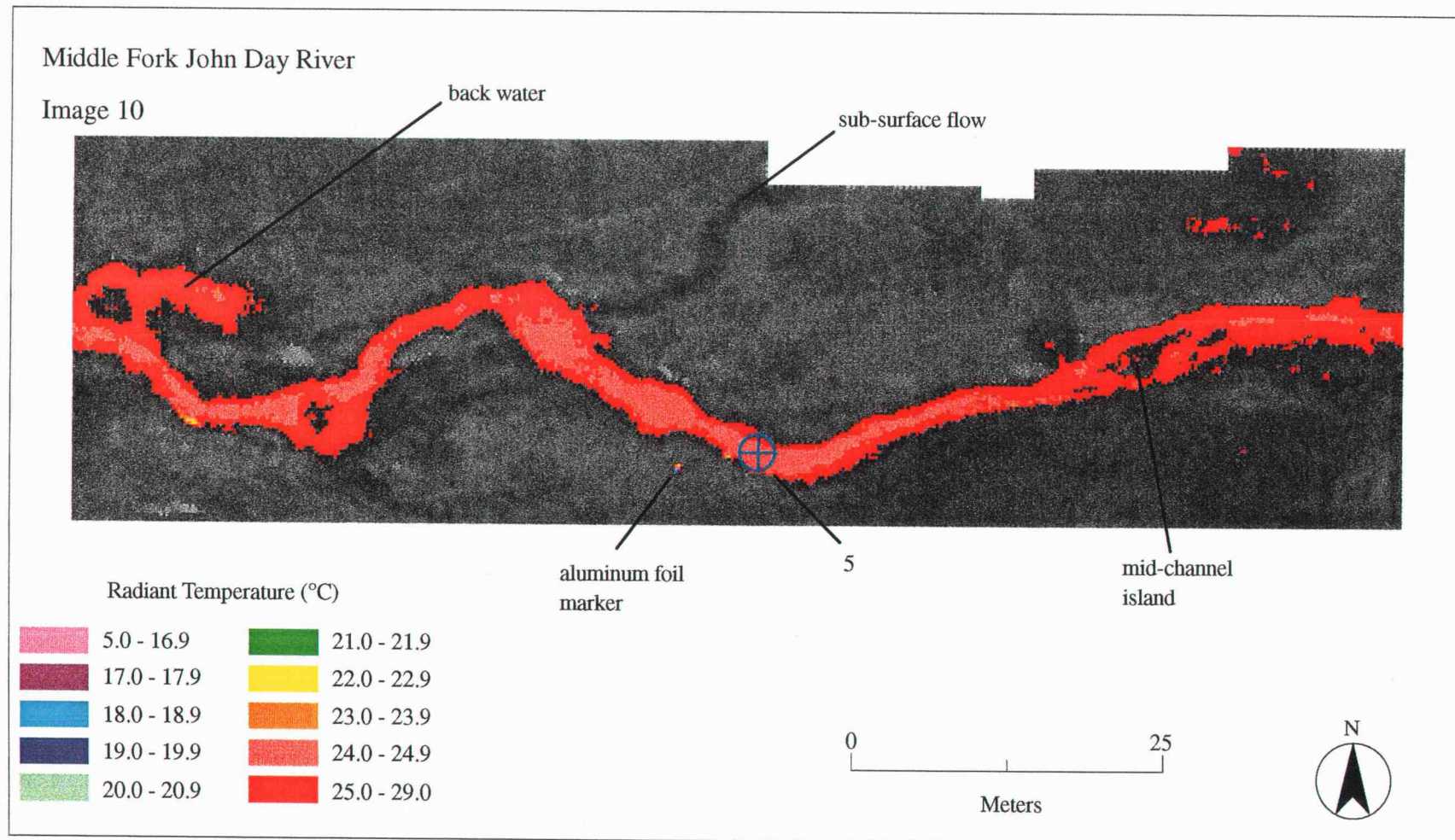


Figure 13. Thermal image (10) of the Middle Fork John Day River, upstream of Clear Creek. Blue circle shows approximate location of holding salmon. Numbers in the margins indicate the number of salmon observed in each location. Direction of flow is page right to page left. Temperatures greater than 29° C are shown in gray tones (lighter is hotter).

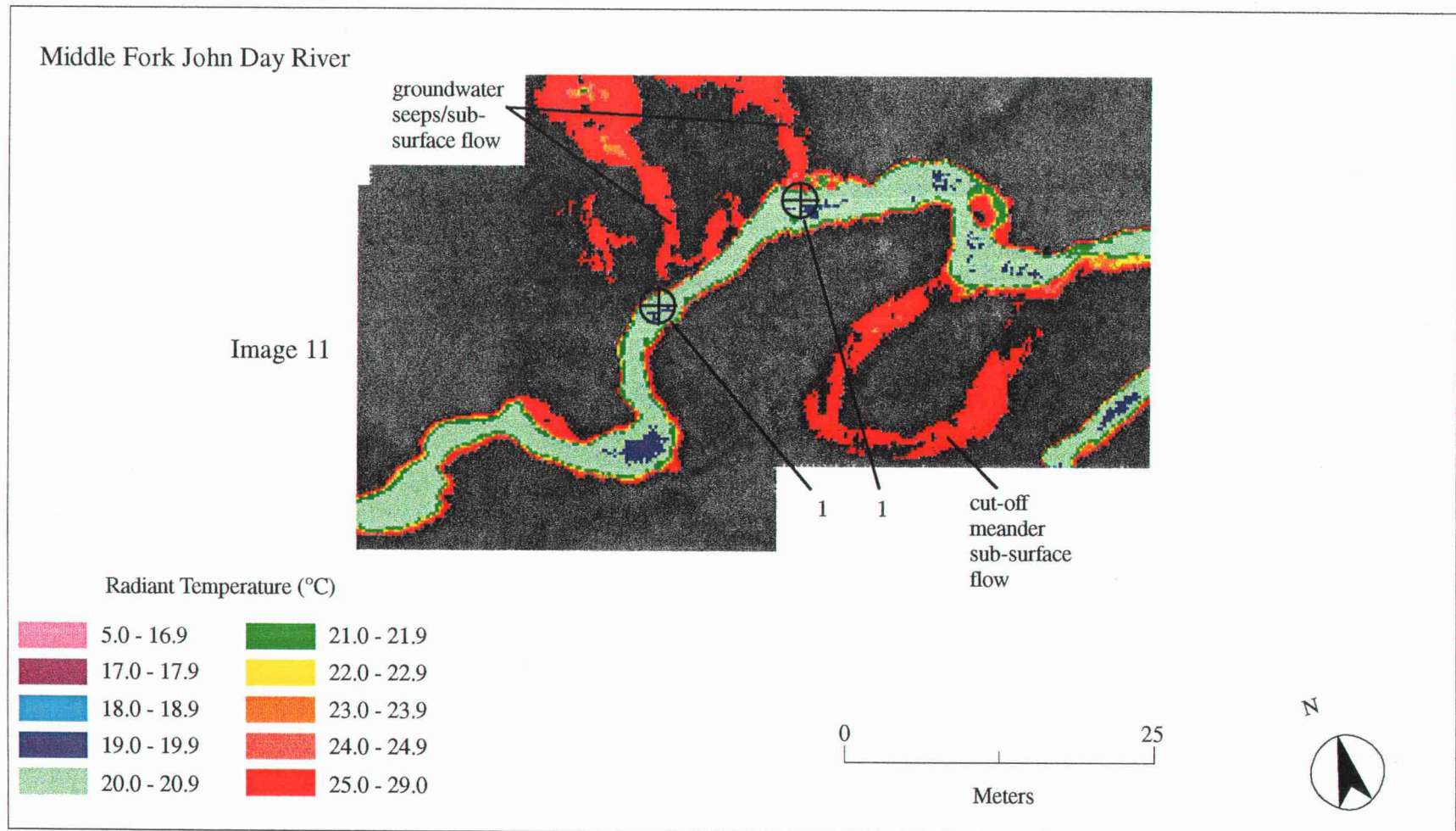
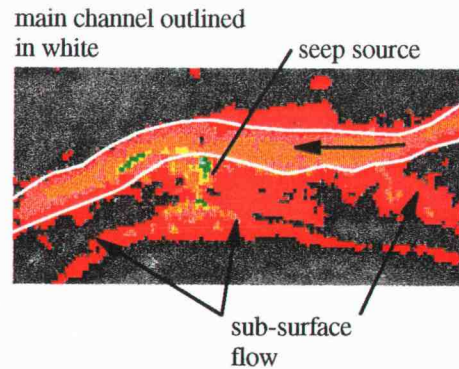


Figure 14. Thermal image (11) of the Middle Fork John Day River, upstream of Crawford Creek. Black circles show approximate locations of holding salmon. Numbers in the margins indicate the number of salmon observed in each location. Direction of flow is page right to page left. Temperatures greater than 29° C are shown in gray tones (lighter is hotter).



# Middle Fork John Day River

Image 12



0 25  
Meters



Radiant Temperature (°C)

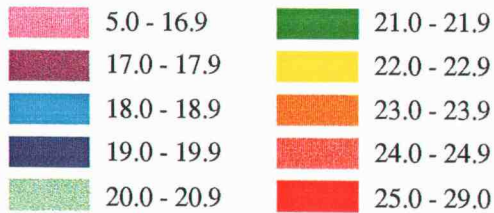
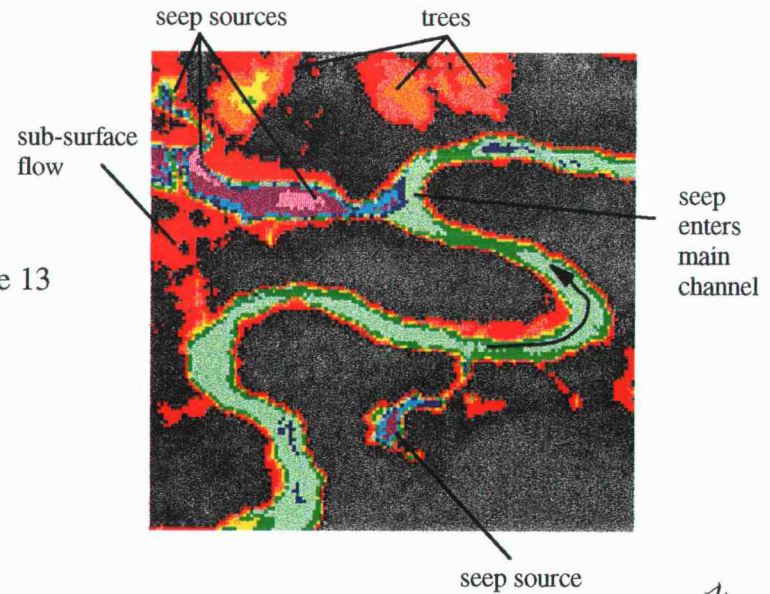


Image 13



0 30  
Meters



Figure 15. Thermal images (12 and 13) of the Middle Fork John Day River, examples of cool-water inputs and associated sub-surface flow patterns. Dark red color indicates soil surface with sub-surface water pathways. Temperatures greater than 29° C are shown in gray tones (lighter is hotter). Direction of stream flow is depicted by black arrows.

### Reach Level Patterns

In the North Fork study reach, peaks in salmon numbers did not correspond consistently with low stream temperatures (Figure 16). Salmon were dispersed throughout the study reach in approximately normal distribution (i.e., with low numbers in both the highest and lowest temperature zones). The majority (83%) of the salmon in the North Fork were clustered at densities higher than the overall reach density, and there were no significant ( $p > 0.05$ ) associations between patchiness in salmon numbers and stream gradient, water temperature, or width-depth ratio (Table 12). In the upper North Fork, stream temperature does not appear to be a factor limiting the distribution of holding salmon. Therefore, other stream habitat characteristics may be more influential in determining reach selection by salmon. For example, spatial patterns of pool volume were significantly related ( $p < 0.0002$ ) to the distribution of salmon. The greatest proportion (49%) of salmon in the North Fork were located in reaches with greater than expected pool volume. The number of pools greater than 0.7 m in depth was not significantly associated with spatial patterns of water temperature, but there was a highly significant ( $p < 0.0001$ ) indirect relationship between stream gradient and water temperature (i.e., low gradient reaches were significantly warmer than steep reaches).

Stream temperature patterns and salmon numbers in Granite Creek/Clear Creek showed closer associations than were observed in the North Fork (Figures 17 and 18). During the holding survey, 82% of the salmon were clustered at densities higher than the overall reach density, and 67% of the salmon were observed in reaches with lower than expected stream temperature (Table 13). Patchiness in the distribution of holding salmon and water temperature patterns were not significantly related at the 0.05 significance level. However, there was a highly significant relationship ( $p < 0.0001$ ) between spawning salmon and temperature patterns (i.e., more salmon were located in reaches with relatively lower stream temperatures). In Granite Creek/Clear Creek, contingency table analysis indicated that patchiness in stream gradient, width-depth ratio, and pool volume were significantly associated with the distribution of holding salmon, whereas patchiness in stream

temperature, width-depth ration, and pool volume were significantly associated with the distribution of spawning salmon (Table 13). Surface water inputs were significantly associated ( $p < 0.05$ ) only with pool volume. Fisher's exact test showed a nonsignificant relationship between stream gradient and spawning salmon. However, eighty-two percent of the spawning salmon in the study reach were located in reaches with lower than expected stream gradient, so the majority of salmon were selecting low gradient habitats.

Compared to the North Fork and Granite Creek/Clear Creek study reaches, the distribution of salmon in the Middle Fork was the most significantly associated with patterns of stream temperature. Seventy-eight percent of the salmon holding in the Middle Fork were clustered at densities higher than the overall reach density, and the greatest proportion (78%) of salmon were located in reaches where stream temperature was less than expected (Table 14). The two highest peaks (river kilometer 89 and 101) in salmon density in the Middle Fork corresponded to distinct troughs in the stream temperature profile (Figures 19 and 20). Other habitat variables that were significantly associated ( $p < 0.05$ ) with salmon numbers were stream gradient and pool volume. Of the stream habitat variables, stream gradient appeared to be the major factor influencing the distribution of salmon in the Middle Fork, especially considering that the 2 km reach containing the highest density of salmon was also the lowest gradient section (river kilometer 99-103) in the entire Middle Fork study reach. The distribution of surface water inputs, in contrast to Granite Creek/Clear Creek, was significantly related ( $p < 0.05$ ) to patchiness in both stream temperature and pool volume. The greatest proportion of surface water inputs occurred where stream temperature was lower than expected, indicating either a cooling effect of surface water inputs on stream temperature or crosscorrelation with valley hydrogeologic features. Contingency table analysis of stream temperature in the Middle Fork also revealed a highly significant, direct association ( $p < 0.0001$ ) with width-depth ratio, but there was no significant association between the number of pools ( $\geq 0.7$  m in depth) and spatial patterns of stream temperature.

Figure 16. Longitudinal spatial patterns of spring chinook salmon and habitat variables in the North Fork John Day River, 1994. Stream temperature patterns represent peak daily water temperature on August 8, 1994. The spatial scale of analysis is 1 km. From top to bottom, variables plotted against river kilometer include total number of holding salmon, mean width-depth ratio, total volume of pools  $\geq 0.7$  meters in depth, stream gradient, and time-corrected stream temperatures obtained from thermography. Solid lines connecting data points indicate the longitudinal extent of surveys. Dashed vertical lines denote the location of peaks in the number of holding salmon. Dashed horizontal lines denote densities and means for salmon and habitat variables. Refer to Table 5 for derivations of densities and means. See Tables 6 and 9 for more detailed information on fish and habitat surveys.

Figure 16.

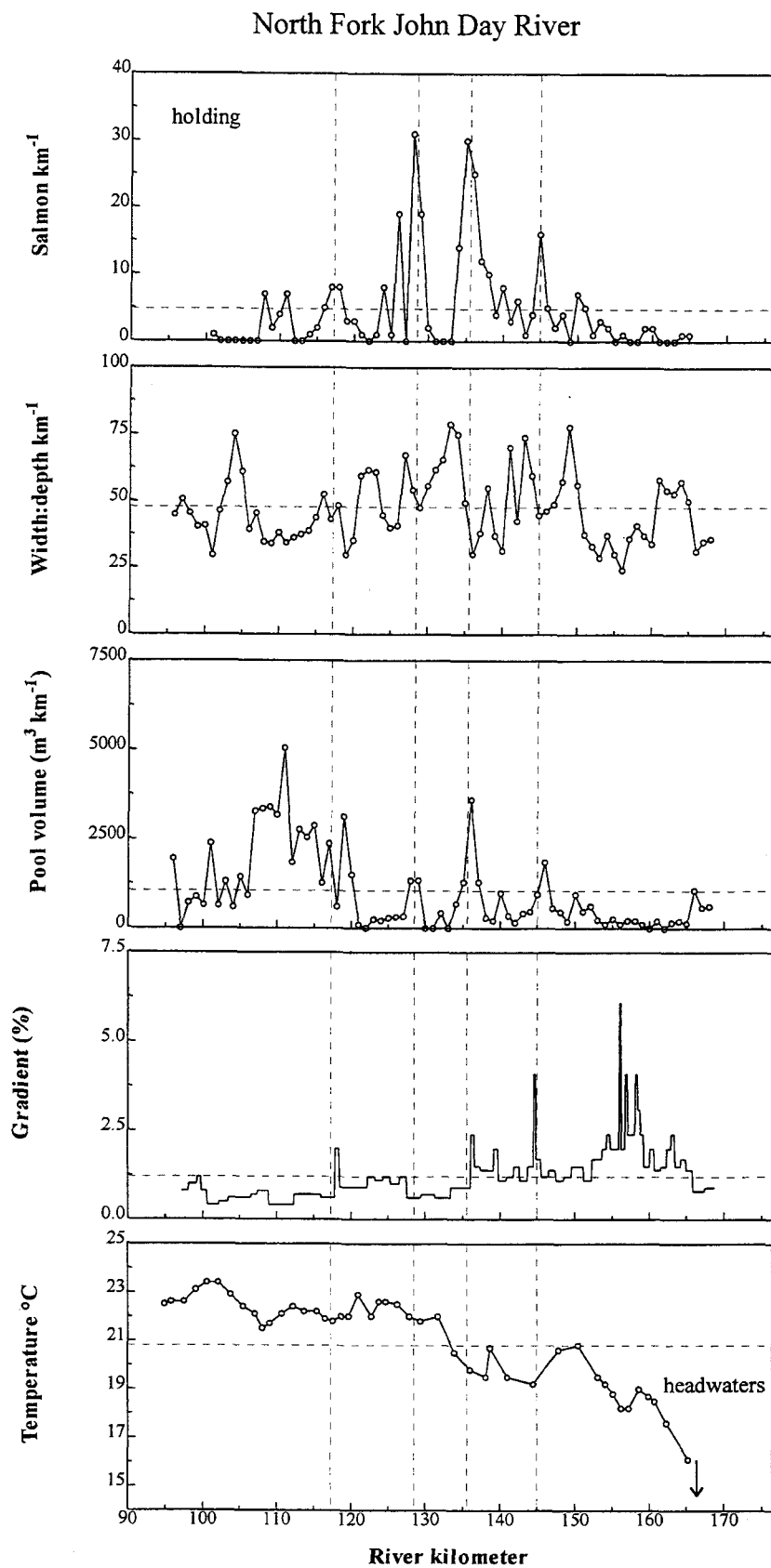


Table 12. Contingency tables of salmon number and stream habitat variables in the North Fork John Day River. Two-tailed P-values (*P*) indicate the strength of patch association between compared variables. Expected (*E*) and observed (*O*) values for number of salmon and habitat variables are displayed in Table 5.

	Holding salmon (no.)		Pools <sup>a</sup> (no.)		Width:depth (no. of cases)		Water temperature (no. of cases)	
	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>
Stream Gradient								
<i>O</i> > <i>E</i>	102	25	68	37	15	18	4	28
<i>O</i> < <i>E</i>	148	27	113	28	15	23	32	3
<i>P</i>	0.3568		0.0084		0.6379		<0.0001	
Water temperature								
<i>O</i> > <i>E</i>	112	21	105	40	16	21		
<i>O</i> < <i>E</i>	138	30	53	26	14	17		
<i>P</i>	0.7573		0.4444		1.000			
Width:depth								
<i>O</i> > <i>E</i>	105	20	31	36				
<i>O</i> < <i>E</i>	145	32	150	29				
<i>P</i>	0.7572		< 0.0001					
Pool volume								
<i>O</i> > <i>E</i>	149	16						
<i>O</i> < <i>E</i>	101	36						
<i>P</i>	0.0002							

<sup>a</sup> Includes pools with maximum depth  $\geq 0.7$  meters.



Figure 17. Longitudinal spatial patterns of spring chinook salmon and habitat variables in Granite Creek and Clear Creek (North Fork John Day River subbasin), 1994. Stream temperature patterns represent peak daily water temperature on August 8, 1994. The spatial scale of analysis is 1 km. From top to bottom, variables plotted against river kilometer include total number of holding and spawning salmon, total number of seeps and tributaries, stream gradient, and time-corrected stream temperatures obtained from thermography. Solid lines connecting data points indicate the longitudinal extent of surveys. Dashed vertical lines denote the location of peaks in the number of holding salmon. Dashed horizontal lines denote densities and means for salmon and habitat variables. Refer to Table 5 for derivations of densities and means. See Tables 6 and 9 for more detailed information on fish and habitat surveys.

Figure 17.

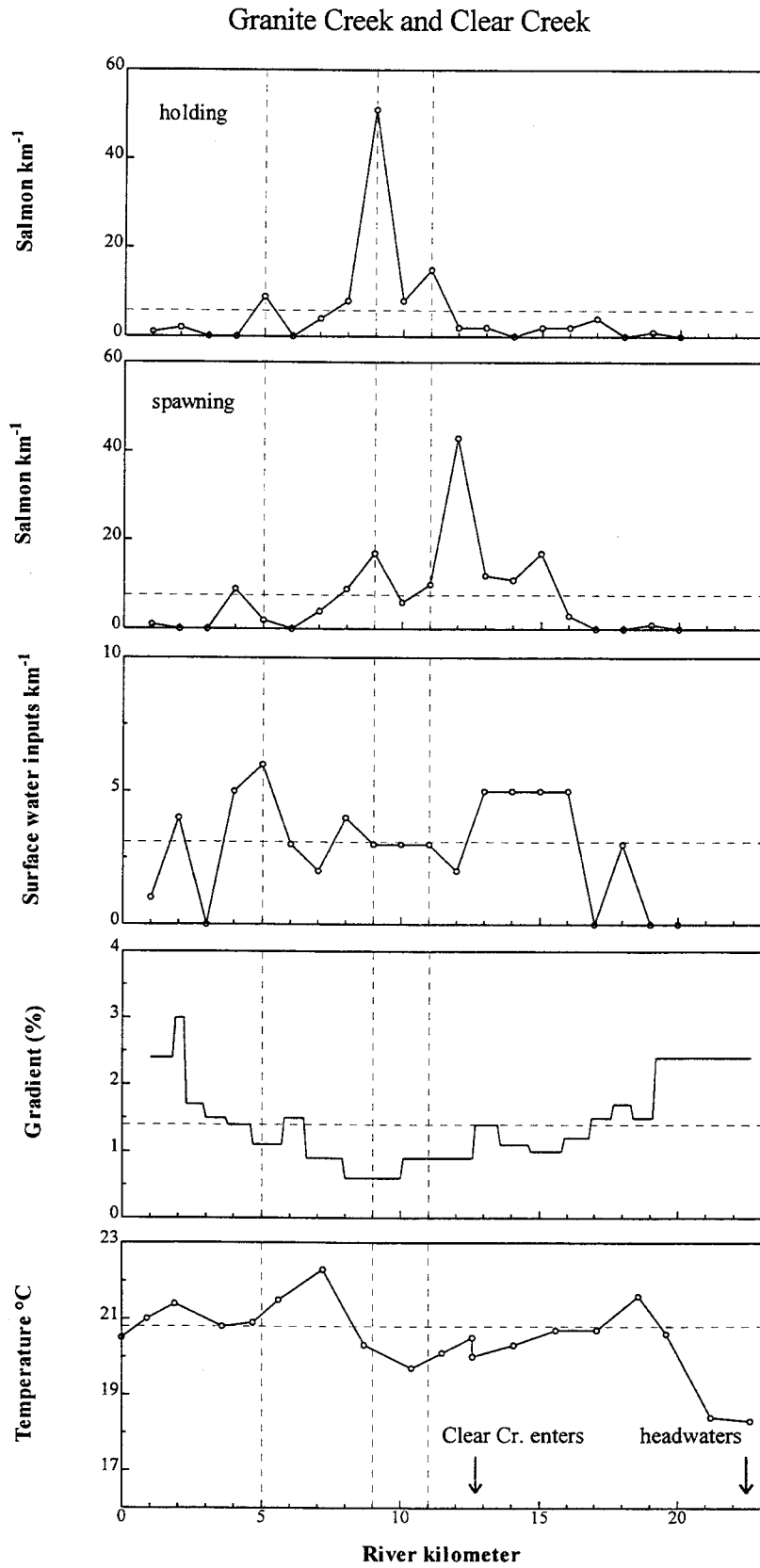


Figure 18. Longitudinal spatial patterns of spring chinook salmon and habitat variables in Granite Creek and Clear Creek (North Fork John Day River subbasin), 1994. Stream temperature patterns represent peak daily water temperature on August 8, 1994. The spatial scale of analysis is 1 km. From top to bottom, variables plotted against river kilometer include total number of holding and spawning salmon, mean width-depth ratio, total volume of pools  $\geq 0.7$  meters in depth, and time-corrected stream temperatures obtained from thermography. Solid lines connecting data points indicate the longitudinal extent of surveys. Dashed vertical lines denote the location of peaks in the number of holding salmon. Dashed horizontal lines denote densities and means for salmon and habitat variables. Refer to Table 5 for derivations of densities and means. See Tables 6 and 9 for more detailed information on fish and habitat surveys.

Figure 18.

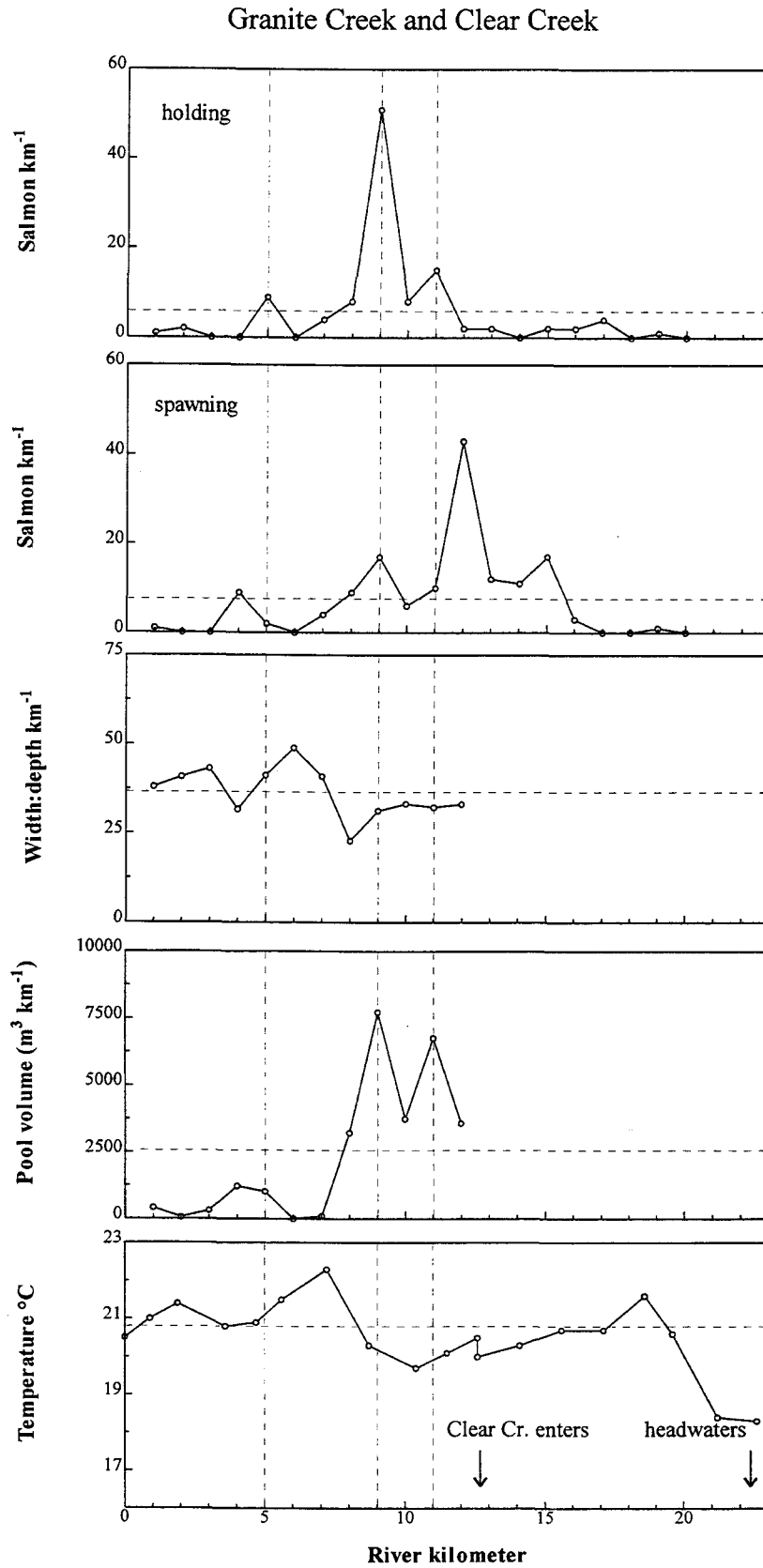


Table 13. Contingency tables of salmon number and stream habitat variables in Granite Creek/Clear Creek (North Fork subbasin). Two-tailed P-values (*P*) indicate the strength of patch association between compared variables. Expected (*E*) and observed (*O*) values for number of salmon and habitat variables are displayed in Table 5.

	Holding salmon (no.)		Spawning salmon (no.)		Surface inputs <sup>a</sup> (no.)		Pools <sup>b</sup> (no.)		Width:depth (no. of cases)		Water temperature (no. of cases)	
	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>
Stream Gradient												
<i>O</i> > <i>E</i>	0	8	9	2	9	7	6	10	4	1	6	3
<i>O</i> < <i>E</i>	91	12	119	15	30	13	44	5	2	5	3	8
<i>P</i>	< 0.0001		0.6188		0.3658		< 0.0001		0.2424		0.1748	
Water temperature												
<i>O</i> > <i>E</i>	17	8	9	8	14	9	6	15	6	1		
<i>O</i> < <i>E</i>	74	12	119	9	25	11	44	0	0	5		
<i>P</i>	0.0717		< 0.0001		0.5777		< 0.0001		0.0152		—	
Width:depth												
<i>O</i> > <i>E</i>	0	16	0	7	10	6	0	15				
<i>O</i> < <i>E</i>	66	18	70	24	9	11	50	0				
<i>P</i>	< 0.0001		0.0002		0.3351		< 0.0001		—		—	
Pool volume												
<i>O</i> > <i>E</i>	66	18	70	15	4	11						
<i>O</i> < <i>E</i>	0	16	0	16	15	6						
<i>P</i>	< 0.0001		< 0.0001		0.0166		—		—		—	
Surface inputs												
<i>O</i> > <i>E</i>	17	8	58	5								
<i>O</i> < <i>E</i>	74	12	70	12								
<i>P</i>	0.0717		0.2989		—		—		—		—	

<sup>a</sup> Surface water inputs include tributary confluences, seeps, and irrigation return flow.

<sup>b</sup> Includes pools with maximum depth ≥ 0.7 meters.



Figure 19. Longitudinal spatial patterns of spring chinook salmon and habitat variables in the Middle Fork John Day River, 1994. Stream temperature patterns represent peak daily water temperature on August 5, 1994. The spatial scale of analysis is 1 km. From top to bottom, variables plotted against river kilometer include total number of holding and spawning salmon, total number of seeps, tributaries and irrigation inputs, stream gradient, and time-corrected stream temperatures obtained from thermography. Solid lines connecting data points indicate the longitudinal extent of surveys. Dashed vertical lines denote the location of peaks in the number of holding salmon. Dashed horizontal lines denote densities and means for salmon and habitat variables. Refer to Table 5 for derivations of densities and means. See Tables 6 and 9 for more detailed information on fish and habitat surveys.

Figure 19.

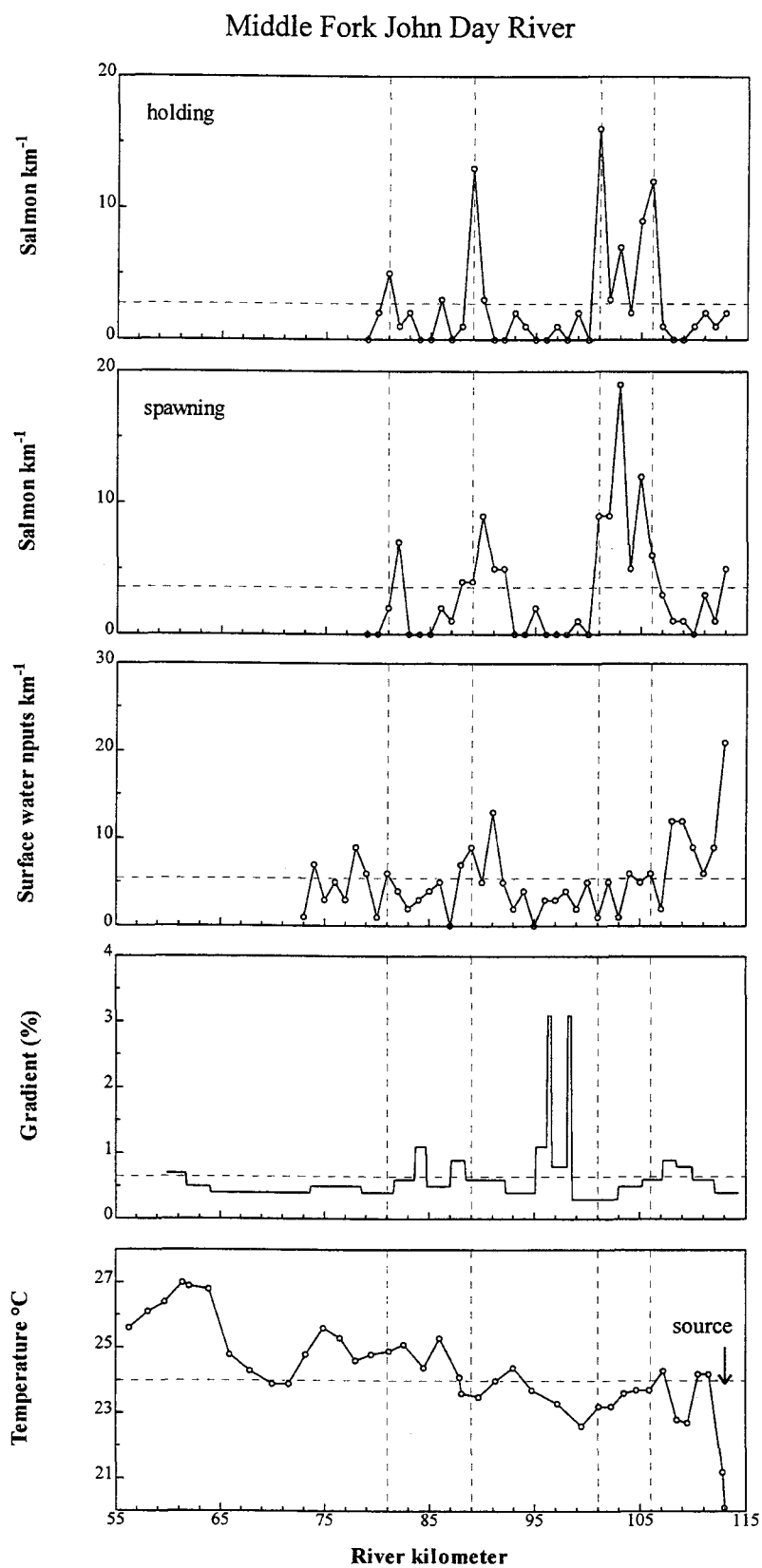


Figure 20. Longitudinal spatial patterns of spring chinook salmon and habitat variables in the Middle Fork John Day River, 1994. Stream temperature patterns represent peak daily water temperature on August 5, 1994. The spatial scale of analysis is 1 km. From top to bottom, variables plotted against river kilometer include total number of holding and spawning salmon, mean width-depth ratio, total volume of pools  $\geq 0.7$  meters in depth, and time-corrected stream temperatures obtained from thermography. Solid lines connecting data points indicate the longitudinal extent of surveys. Dashed vertical lines denote the location of peaks in the number of holding salmon. Dashed horizontal lines denote densities and means for salmon and habitat variables. Refer to Table 5 for derivations of densities and means. See Tables 6 and 9 for more detailed information on fish and habitat surveys.

Figure 20.

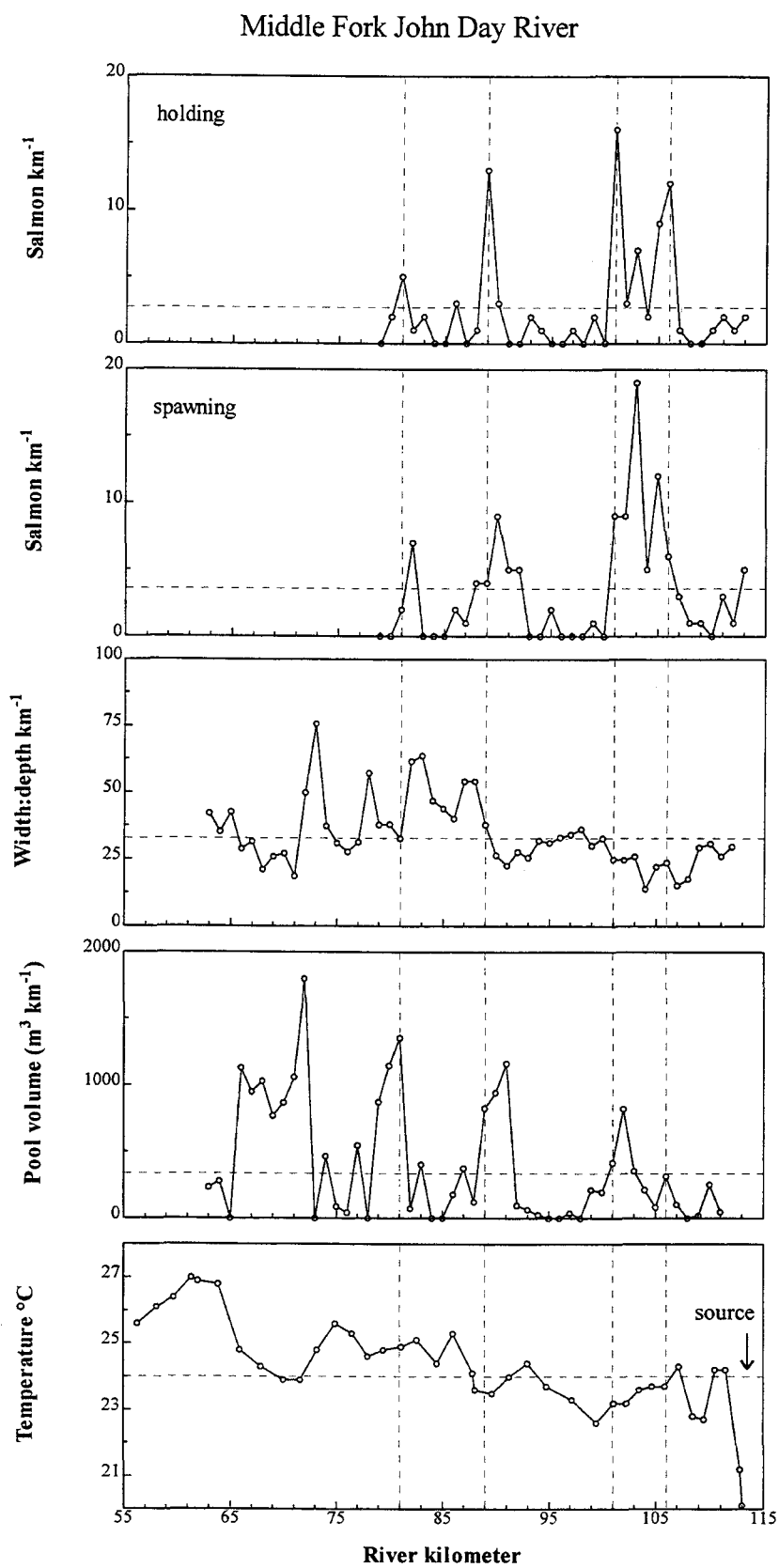


Table 14. Contingency tables of salmon number and stream habitat variables in the Middle Fork John Day River. Two-tailed P-values (*P*) indicate the strength of patch association between compared variables. Expected (*E*) and observed (*O*) values for number of salmon and habitat variables are displayed in Table 5.

	Holding salmon (no.)		Spawning salmon (no.)		Surface inputs <sup>a</sup> (no.)		Pools <sup>b</sup> (no.)		Width:depth (no. of cases)		Water temperature (no. of cases)	
	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>	<i>O</i> > <i>E</i>	<i>O</i> < <i>E</i>
Stream Gradient												
<i>O</i> > <i>E</i>	0	4	4	6	68	19	21	15	6	12	6	14
<i>O</i> < <i>E</i>	71	15	90	11	49	24	63	13	12	19	17	16
<i>P</i>	0.0015		0.0008		0.1520		0.0092		0.7668		0.1593	
Water temperature												
<i>O</i> > <i>E</i>	8	12	27	11	34	40	25	12	14	8		
<i>O</i> < <i>E</i>	63	9	72	6	104	38	59	16	4	24		
<i>P</i>	< 0.0001		0.004		< 0.0001		0.2476		< 0.0001			
Width:depth												
<i>O</i> > <i>E</i>	16	7	15	5	38	24	13	13				
<i>O</i> < <i>E</i>	55	14	84	12	79	54	71	15				
<i>P</i>	0.3907		0.1691		0.8757		0.0016					
Pool volume												
<i>O</i> > <i>E</i>	47	4	61	3	57	8						
<i>O</i> < <i>E</i>	24	14	33	13	86	35						
<i>P</i>	0.0011		0.0008		0.0108							
Surface inputs												
<i>O</i> > <i>E</i>	30	9	29	8								
<i>O</i> < <i>E</i>	41	12	70	9								
<i>P</i>	1.000		0.1659									

<sup>a</sup> Surface water inputs include tributary confluences, seeps, and irrigation return flow.

<sup>b</sup> Includes pools with maximum depth  $\geq 0.7$  meters.

\* P-value from chi-squared non-parametric test. All other P-values were calculated using Fisher's exact test.



## DISCUSSION

Several recent studies have sought to identify the use of cool-water refugia by trout and salmon (Berman and Quinn 1991, Nakamoto 1994, Matthews et al. 1994, Nielsen et al. 1994). Interest has been focused typically on cold pools and microhabitats utilized by salmonid fishes when ambient water temperatures exceed upper levels of tolerance. The presence of such thermal refugia in streams subject to high summer temperatures and seasonally low flows may explain the continued existence of cold-water fishes in warmwater ( $> 25^{\circ}\text{C}$ ) environments. As a complement to investigations of thermal refugia at microhabitat and channel unit levels, we examined temperature patterns across subunit, channel unit, reach, and landscape spatial scales. Thermal remote sensing enabled us to assess multiscale patterns of stream surface temperature and to identify cool-water areas needing more detailed ground-based examination.

### Summary of Major Findings

Spring chinook salmon were distributed disproportionately throughout each of the North Fork, Granite Creek/Clear Creek, and Middle Fork study areas, indicating that salmon preferred certain reaches within each subbasin. In the Middle Fork and Granite Creek/Clear Creek subbasins, the majority of salmon elected to hold and spawn in low gradient, unconstrained reaches, whereas in the upper North Fork where alluvial valleys were not available, salmon selected both high and low gradient reaches primarily within the North Fork John Day Wilderness. In all three subbasins, pools were the most selected habitat by adult spring chinook. However, among the three streams, riffles were used the most extensively in the North Fork, the coldest subbasin.

Landscape level stream temperature patterns, as expected, showed an overall downstream warming trend. However, inter-reach variation in thalweg temperature on the order of  $2\text{--}3^{\circ}\text{C}$  occurred in all three subbasins. The coldest reaches available to salmon within the Middle Fork and Granite Creek/Clear Creek study areas were situated in low gradient, unconstrained reaches where the cooling influence of groundwater flow was the

most apparent. We observed that the degree of behavioral thermoregulation by salmon depended entirely on the spatial scale of temperature comparisons, particularly in the Middle Fork where stream temperature was the most variable. In the Middle Fork for example, water temperature differences were typically 1-2°C within riffle-pool sequences and 3-4°C among reaches. The reach level association between salmon distribution and stream temperature patterns at channel unit and reach level spatial scales was strongest in the warmest study reach, the Middle Fork, and weakest in the coldest study reach, the North Fork.

### **Thermal Refugia at Multiple Spatial Scales**

Spring chinook salmon continue to exist in the upper Middle Fork John Day River in spite of maximum daily temperatures that exceed 25°C, the upper lethal limit for adult chinook salmon. In an effort to understand how salmon in the Middle Fork cope with high stream temperatures, we used the technique of Berman and Quinn (1991) to tag adult salmon with internal, temperature-sensitive radio transmitters and track their movements with respect to ambient water temperature patterns (Price 1996). Our expectations, based on the findings of Gibson (1966) and Kaya et al. (1977), were that salmon utilized cold tributary confluences, cold pools, and pockets of cool water adjacent to the main stream. Nielsen et al. (1994), for example, observed juvenile and adult steelhead (*Oncorhynchus mykiss*) in cold pools where surface water temperatures were 3-9°C warmer than those at the bottom, and Berman and Quinn (1991) reported that adult chinook salmon behaviorally thermoregulated to maintain internal temperatures 2.5°C cooler than ambient water temperatures.

Contrary to our expectations, preliminary analysis of salmon behavior conducted by Price (1996) at microhabitat spatial scales suggested that salmon in the Middle Fork were not behaviorally thermoregulating, even during a particularly warm summer (water temperatures reached 29°C in exposed stream reaches). The preliminary conclusion, therefore, was that chinook salmon were not behaviorally thermoregulating in the Middle Fork John Day River because they were either adapted to high water temperature, or cold-

water habitats were simply not available. Indeed, pools in the Middle Fork were not thermally stratified like the pools 5 m in depth mentioned by Nielsen et al. (1994). However, analysis of thermal imagery from the same summer revealed that the reaches containing the greatest number of salmon were relatively cold reaches. Even within small-scale pool-riffle sequences, the extent to which we perceived thermoregulatory behavior by salmon depended directly on where main channel temperatures were sampled.

Specifying the spatial scale of analysis is critical in studies of behavioral thermoregulation by fishes in the natural environment. A thermal refuge is defined by the temperature difference between the coldest region within a refuge and the surrounding habitat. Stream temperatures are spatially autocorrelated; therefore, the degree, or significance, of behavioral thermoregulation depends entirely on the locations to which fish temperatures are compared. For this reason it is useful to examine extensive temperature patterns within and among stream reaches before concluding that fish are responding, or not responding, to temperature patterns.

In the study by Berman and Quinn (1991), continuously recording temperature monitors were used to compare fish temperatures to main stream temperature. This is a useful technique for examining the behavior of fish with respect to stream temperature over long periods of time. However, because the specific locations of the temperature monitors were not described in relation to the locations of salmon, differences between focal temperatures and main stream temperatures were difficult to interpret. For example, were the temperature monitors moved daily and placed in the thalweg adjacent to salmon, or were they placed systematically throughout the study reach? These are salient questions that should be addressed in detail before one can conclude that salmon were selecting cooler habitats. Thermal imagery is particularly useful in this situation because it can guide the placement of temperature monitors for subsequent comparison to fish focal temperatures. The disadvantage of remote sensing approaches is that one acquires only a snapshot in time of stream temperature patterns. Therefore, it is necessary to integrate temporally continuous, but spatially limited, temperature monitor data with spatially continuous, but temporally constrained, thermal imagery.

## Habitat Selection

Resource selection by animals is determined by comparing the use of a particular resource or habitat by an animal with its availability in the natural environment. Data on resource use are relatively simple to obtain and can be quantified using non-biased procedures (White and Garrot 1990). However, determining the habitat available to a particular individual is often highly subjective (Manly et al. 1993). Our addressed the use and availability of cool-water areas and stream habitat by spring chinook salmon. Determining what was available to salmon was difficult because seasonal low flow conditions prevented the movement of salmon between reaches containing thermal refugia, and movement patterns of salmon were limited during the summer holding phase when stream temperatures were the highest.

The coldest overall reach temperatures in the North Fork, Granite Creek/Clear Creek, and the Middle Fork were located in the headwaters of each subbasin. Theoretically, if temperature were the primary determinant of habitat selection, salmon would be clustered in these reaches, especially in the North Fork where headwater reaches were accessible throughout the summer. The assumption regarding the North Fork salmon, then, is that stream temperatures below a certain threshold would be selected equally in the absence of other habitat factors. In the Middle Fork, the combination of water removal for irrigation and low mid-summer flows effectively made passage to headwater reaches physically impossible for salmon. The cold headwaters of Clear Creek, the main tributary of Granite Creek, were also inaccessible to salmon because the main channel had dried up by mid-summer. The salmon that occupied headwater locations during the summer most likely arrived in the spring when flows were sufficient.

Results from two years of radio telemetry in the John Day River system indicate that spring chinook have a small summer home range, limited most frequently to a single channel unit (McIntosh et al. unpublished data, Price 1996). An adult spring chinook salmon residing throughout the summer in freshwater is operating on a limited energy budget. Ceasing to feed in freshwater, it lives off its own protein and fat reserves, so

reproductive success and survival depend on the ability of the salmon to conserve energy prior to and in preparation for spawning (Berman and Quinn 1991). Therefore, the energetic costs of mid-summer searches for cool-water areas are likely to be prohibitive for salmon in warmwater environments.

Summer holding habitats were selected in the spring when stream temperatures were low and stream flow was high, so habitats must have been selected based on criteria independent of stream flow and temperature. Use of pool habitats is an effective adaptation by spring chinook, especially in the Middle Fork, where pools are the only form of small-scale thermal refuge available. Relatively deep pools are geomorphically recognizable independent of stream flow, and suitable spawning gravels typically accumulate downstream of pool margins. Large, deep pools are generally considered the primary freshwater holding habitat used by chinook throughout their range (Healey 1991). However, preliminary results from Price (1996) showed that chinook occupied riffle habitats more frequently in cold streams than in warm streams in northeastern Oregon. The study by Price (1996) also acknowledged the influence of other habitat characteristics in addition to stream temperature on freshwater habitat selection by chinook salmon.

Pools alone are not the primary determinant of habitat selection. It is interesting to note that the highest reach density of large pools (depth  $\geq 0.7$  m) in both the North Fork and Middle Fork occurs downstream of the reaches occupied by salmon. Stream temperatures in these downstream reaches exceed the tolerance level for spring chinook, thus rendering numerous downstream pool habitats inaccessible to salmon. This indicates that tradeoffs between pool availability and stream temperature may play important roles in determining the longitudinal extent of spring chinook holding habitat.

## **Reach Selection**

Resource selection by fishes occurs across multiple spatial and temporal scales. Bayley and Li (1992) noted that resource selection can follow a hierarchy of habitat scales, with selection in each order being conditional on higher (small-scale) or lower

(large-scale) orders. For example, during the summer, spring chinook in the Middle Fork were significantly associated with relatively cold reaches; however, the salmon migrated in the spring and actual habitat selection at that time was more likely based on physical reach characteristics and chemical cues, because water temperatures were far below summer maxima. Once within a reach of choice, the salmon sought cover, such as pools, undercut banks, and thermal refugia if they were available, at channel unit and subunit levels.

Anadromous salmonids have demonstrated an ability to return to home streams and tributaries by following chemical concentration gradients to locate the same "kind" of water in which they emerged and matured (Johannesson 1982, Thorpe 1988). In marginal habitats such as the Middle Fork, the ability to locate limited habitats suitable for holding and spawning in 100 km of river is critical for survival. Suitable spawning habitat is even more limited in most rivers than superficial observation may suggest because chinook require subgravel flow to aerate eggs requiring high dissolved oxygen levels (Burger et al. 1985, Healey 1991). Thorpe (1994) points out that the high homing accuracy of adult salmonids to their natal streams can either function as insurance, such as in the Middle Fork, or lead to extinction of stocks in the event of localized environmental disturbances. It is likely that the varied age structure and straying tendencies of spring chinook among the Middle Fork, North Fork, and main stem John Day River have also played a role in protecting John Day salmon stocks against extinction, particularly during past years of extensive dredge mining.

In the absence of human disturbances to the landscape, unconstrained reaches in the upper Middle Fork probably functioned in the past even more effectively as reach level refugia for spring chinook (Sedell et al. 1990). Wide alluvial valleys with multiple pool/riffle sequences and complex side-channel/backwater habitats increase the potential for cool-water retention and cold pool formation (Ebersole 1994). These complex floodplain features are apparent in the Middle Fork only as relics visible in aerial photographs and thermal imagery, but in some reaches the hydrogeologic template still buffers the stream ecosystem against human perturbations such as grazing and channelization. For example, in the holding and spawning reaches of the Middle Fork,



approximately 40 km upstream of Big Creek, water temperatures were at least 3-4°C cooler than downstream habitats, and groundwater dynamics appeared to be the principal factor moderating stream temperature. The alluvial valley 2 km downstream of Clear Creek in the upper Middle Fork is one such reach where groundwater dynamics apparently maintain sub-optimal, but tolerable, spawning and holding habitat for chinook salmon in spite of grazing, channelization, and railroad construction.

### **Resource Patchiness in Lotic Systems: Restoration Implications**

The varied spatial and temporal patterns of resource patches comprising a landscape mosaic to which biological organisms respond have long been the focus of terrestrial biogeography and landscape ecology (Brown and Gibson 1983, Forman and Godron 1986). Recent applications of landscape-based models and patch dynamics theory in lotic systems have shown promise for addressing increasingly critical issues of stream habitat fragmentation (Pringle et al. 1988, Grossman et al. 1995). In our study of spring chinook in the John Day River basin, we have identified the problems and also the benefits associated with stream temperature patchiness, or discontinuity, both in currently disturbed and in recovering riverine ecosystems (e.g., the Middle Fork and North Fork John Day River, respectively).

Connectivity among system components in aquatic and terrestrial ecosystems is considered necessary for maintaining long-term ecological health (Naiman et al. 1992, Taylor et al. 1993). However, it is heterogeneity in the landscape/hydrogeologic template that creates refuge patches, which are also vital components of long-term ecological health (Sedell et al. 1990). Our observations of thermal refugia occurring at multiple spatial scales, particularly in the Middle Fork John Day River, indicate that although discontinuity may be an ecological warning sign, resource patches in streams should also be viewed as expressions of restoration potential because they are functioning remnants of a once continuous, intact hydrologic system. This view concurs with recently proposed restoration approaches for streams in the Pacific Northwest by Reeves et al. (1995) and Ebersole (1994) who consider the landscape a dynamic mosaic of varying

habitat conditions, some that are suitable for anadromous salmonids and some that are not, in which restoration should progress as a re-expression of habitat capacity.

The Oregon Department of Environmental Quality (DEQ 1995) specifically addresses the role of spatial and temporal variability and the importance of refugia in the management plan for temperature in Oregon streams. In an effort to consider natural temporal variability and the cumulative effects of sustained high temperature, the DEQ recommended the current temperature standard of 17.8°C, which is the average of the daily maximum temperatures over a moving 7-day period. The remote sensing techniques described in this study have proved highly effective for assessing spatially extensive patterns of stream temperature and locating cool-water refugia. However, aerial thermography is temporally limited and, unlike the current water temperature standard, does not consider temporal variability and the cumulative effects of sustained high water temperatures on aquatic organisms. To optimize stream temperature monitoring and management, remote sensing should be used in conjunction with continuously-recording data loggers in order to obtain a comprehensive view of spatial as well as temporal water temperature patterns.

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